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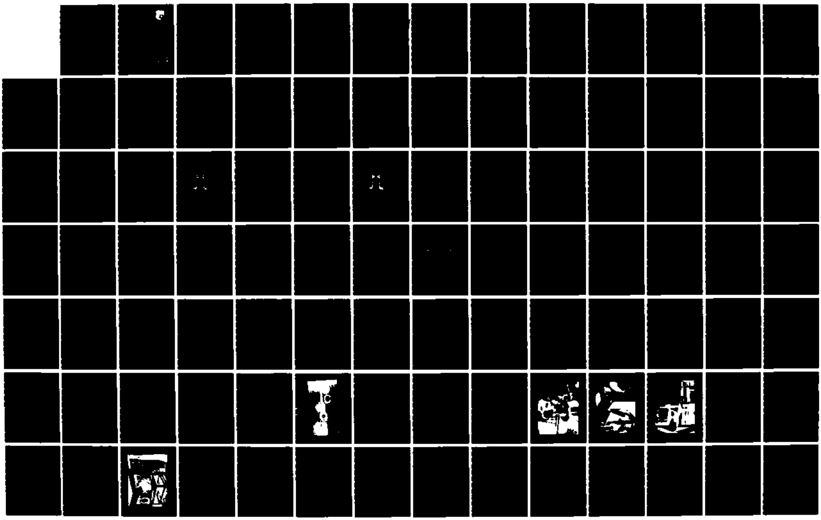

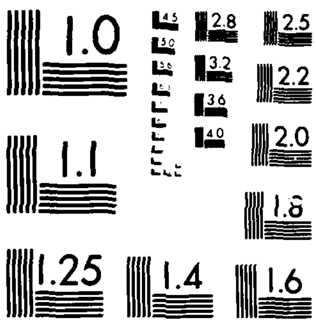

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FIREPROOF HYDRAULIC BRAKE SYSTEM

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The design, development, and manufacture of a flightworthy two-fluid fireproof hydraulic brake system (FHBS) kit for flight testing on a C/KC-135 has been accomplished. The results of system concept trade studies, the concept selection procedure and rational, [illegible] system design analyses, and component and system testing are summarized [illegible]. The FHBS design selected is a two-fluid concept that uses nonflammable chlorotrifluoroethylene (CTFE) in the high fire-potential area of the brake and landing [illegible]. The barrier between the CTFE fluid and the MIL-H-5606 hydraulic fluid is a [illegible] component; a reservoir/separator. Based on the analysis and laboratory testing, it was concluded that the FHBS design is both flightworthy and has braking performance [illegible] the C/KC-135 brake system for runway/tire friction coefficients of 0.2 to [illegible]. It is recommended that the FHBS kit be installed on a C/KC-135 and flight testing [illegible]. Recommendations regarding test conditions and instrumentation for [illegible]

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FOREWORD

This report was prepared by D. W. Huling and H. F. Hillman of the Boeing Military Airplane Company, Seattle, Washington under Air Force Contract F33615-83-C-2322. The work was accomplished under Project Number 31453033, "Fireproof Hydraulic Brake System" during the period from 1 July 1983 to 31 July 1985. Project Engineer for the contract was Mr. W. Bruce Campbell, Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory AFWAL/POOS, Wright-Patterson AFB, Ohio. Technical assistance was provided by Mr. Ed Binns (AFWAL/POOS) and Mr. Alan Whitney (ASD/ENFEM).

The objective of this contract was to design, develop and manufacture a Fireproof Hydraulic Brake System (FHBS) k for flight testing on a C/KC-135 aircraft. The FHBS is a two-fluid system using chlorotrifluoroethylene nonflammable hydraulic fluid in the immediate area of the landing gear and brakes.

Mr. Myles L. Holmdahl served as the overall FHBS Program Manager; Mr. John E. Snyder as FHBS Program Manager (Wichita); Mr. Don W. Huling as Principal Investigator; Mr. H. Floyd Hillman as Simulations Analyst; Mr. Richard L. Howard as Safety Analyst (Wichita); and Mr. Jerry P. Snook, Mr. Randy Schemkes, and Mr. Forrest Richardson, as System Designers (Wichita).

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I. INTRODUCTION

The Air Force's increasing concern over loss of aircraft and personnel to aircraft hydraulic fluid fires has resulted in a program to develop a nonflammable hydraulic fluid and its associated system. The Air Force has, through a series of contracts, determined a nonflammable fluid, the fluid's physical and chemical characteristics, and certain aircraft/fluid acceptability parameters. The fluid selected was Halocarbon Corporation's AO-2, a chlorotrifluoroethylene (CTFE) basestock to which a rust inhibitor additive and a lubricity additive have been added. Although most of the CTFE physical and chemical characteristics are similar to other hydraulic fluids, the CTFE has a 1.8 specific gravity. An excessive hydraulic system weight would result, due to the fluid density, if conventionally designed into an aircraft. Since the majority of hydraulic fluid fires are initiated by hot brakes in the landing gear/wheel well areas, a system design that restricts the use of the CTFE to the brake system minimizes the weight increase while significantly reducing the aircraft fire hazard.

A preceding contract (F33615-80-C-2026 Fireproof Brake Hydraulic System) studied the use of a two-fluid braking system. A C/KC-135 fireproof brake system design was developed, analyzed, and tested. The program did not address the flightworthiness (qualification) testing of the hardware, nor was there an indepth study of the aircraft installation of the modified hardware.

The previous program did show the feasibility of the two-fluid brake system through component and distribution system redesign and laboratory testing. The pressure deboost valve was modified to provide a mechanical separation of the CTFE fluid in the brake system and the MIL-H-5606 fluid in the aircraft hydraulic system. Laboratory tests and computer simulations performed to assess the performance of a two-fluid brake system as compared to the conventional C/KC-135 aircraft brake system noted a significant degradation of stopping performance at certain specific runway friction level conditions. However, computer frequency analysis of the brake hydraulic system indicated that stopping performance equivalency could be achieved through increases in the brake system tubing diameters.

The Air Force initiated the current program, designated Fireproof Hydraulic Brake System (FHBS), to design, evaluate and flightworthiness test an aircraft two-fluid brake system hardware kit that the Air Force would install on a C/KC-135 aircraft and evaluate in flight test. The FHBS program required an initial preliminary design phase followed by final design, analysis, manufacture and test of the kit hardware system.

The specific principle objective of the FHBS program is to develop a two-fluid fireproof brake system that has equivalent or better stopping performance and safety when compared to the existing C/KC-135 Mark II antiskid, five rotor brake system. The program's generalized objective is to show the feasibility of developing hardware for a two-fluid nonflammable braking system for any aircraft.

II. PROGRAM PLAN

The FHBS program plan was developed within the Boeing proposal (Reference 1) to meet the statement of work requirements specified in Air Force Contract F33615-83-C-2322. Program activities were broken down into tasks such that specific areas of expertise within The Boeing Company could be utilized to accomplish these activities in the most cost effective manner.

The preliminary design phase constituted a trade study aimed at determining an optimum CTFE fluid replenishment system, as well as design layouts of the components and system installation and a preliminary hazard analysis. An oral presentation and a Class II Modification Document (Part I) completed the preliminary design activities.

Following Air Force approval for program continuation, Boeing initiated detail component design and manufacture of the FHBS's unique components, ordering of long lead time parts and development of a component flightworthiness test plan. These Seattle activities were coordinated with the Wichita activities of system installation design and system hazard analysis. The design, analysis and test tasks of the FHBS program are shown in Figure 1.

Task 1 - FHBS Design: The prime objective of this task was to evaluate, through a trade study, possible CTFE fluid replenishment systems. Five candidate systems plus two alternative reservoir schemes were evaluated against the "baseline" two-fluid system developed in a prior contract. Information generated from Tasks 2, 3, 4 and 11 was utilized in the development of the trade study.

Task 2 - Frequency Response Analysis: A frequency response analysis of the C/KC-135 brake system, the two-fluid system "baseline", and each of the FHBS candidates (from Task 1) was performed utilizing the AFWAL/APL developed Hydraulic System Frequency Response (HSFR) computer program. The systems were modeled and analyzed from the antiskid valve through the brake assemblies.

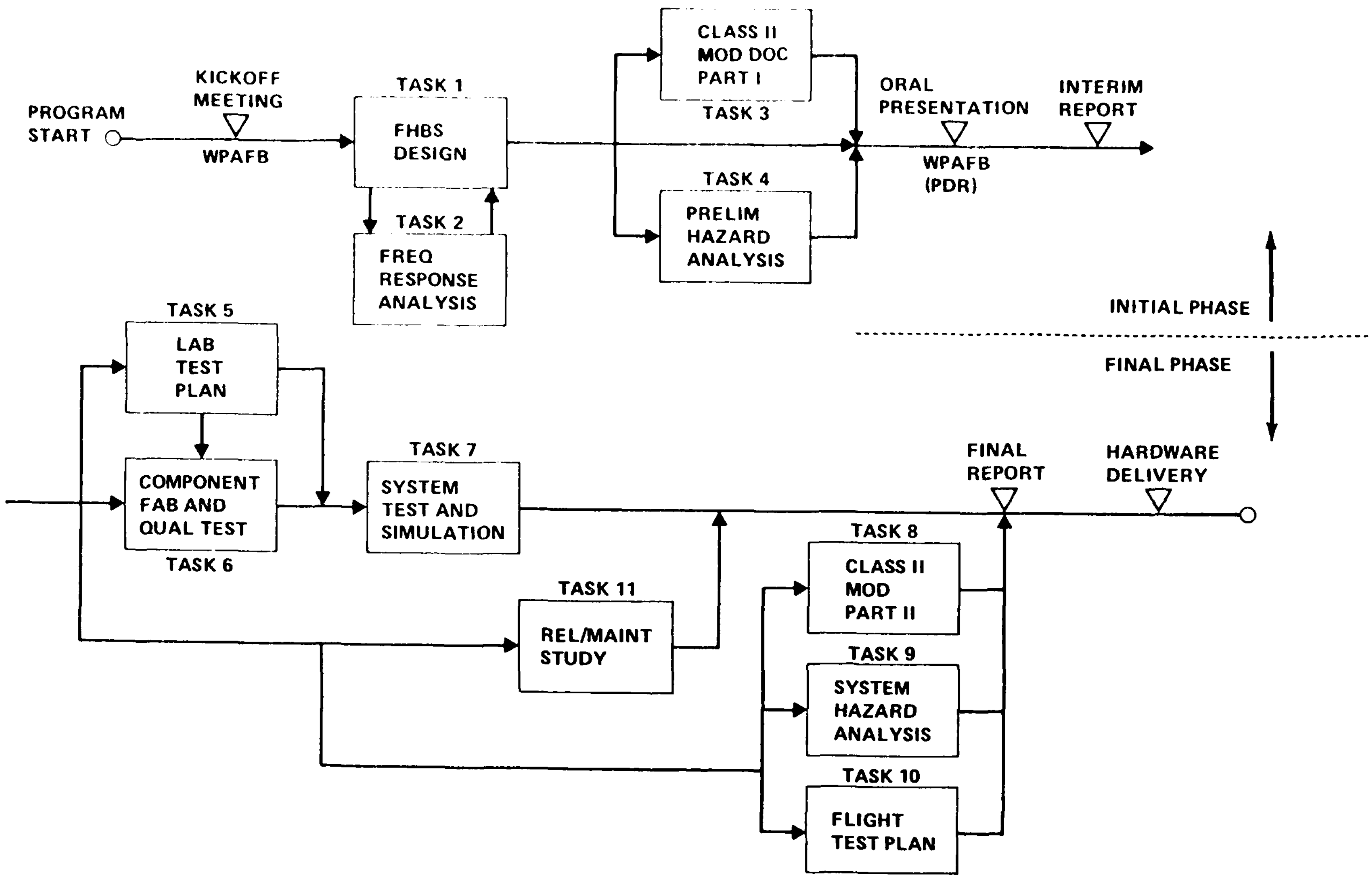


Figure 1. FHBS Initial and Final Phases Tasks

The data generated in this task determined the tubing diameter increase required to achieve a frequency response comparable to the C/KC-135 brake system. Also, the requirement for a one-way restrictor valve was determined during the analysis. These requirements were utilized in Tasks 1 and 3.

Task 3 - Class II Modification Documentation (Part I), Reference 4: This task included the preliminary design, analysis and documentation required for the proposed C/KC-135 aircraft modification and installation. Stress analysis of the FHBS aircraft installation and stress and vibration analyses of the newly designed hydraulic components were conducted. The Class II Modification Document (Part I) was prepared and included preliminary component and system installation designs as well as the supporting analyses. The document presented data developed in Tasks 1, 2, 4 and 11.

Task 4 - Preliminary Hazard Analysis: A Preliminary Hazard Analysis (PHA), Reference 3, was performed on the selected FHBS resulting from the trade study evaluation in Task 1. The PHA determined and recommended changes in the FHBS design to alleviate/reduce any safety problem areas.

Task 5 - Laboratory Test Plans: Laboratory test plans were prepared for component qualification and system flightworthiness tests. All components such as the reservoir/separator, deboost valve, brake assemblies, fill valve and special (FHBS unique) adapters were tested at proof pressure and for leakage to show structural and/or fluid integrity as applicable. In addition, the new/unique components for the FHBS were tested for durability during the system tests.

Vibration tests of the new/unique components were conducted to show the structural durability in an aircraft vibration environment. Vibration tests of the reservoir/separator-deboost valve assembly and installation bracketry were conducted at the Boeing Structural Dynamics Laboratory per Boeing document D-16046 "Vibration Test Requirements for Items of Equipment Installed in Model KC-135 Airplanes."

System testing consisted of two phases: "as-built" C/KC-135 brake system performance tests, and FHBS performance and durability tests. The "as built" C/KC-135 system tests were performed to obtain an accurate performance data

base to which a comparison could be made for FHBS equivalency determination. C/KC-135 system tests consisted of sinusoidal and step response, stopping distance, stepped friction and varied damping ratio gear stability. These performance tests were to be conducted at -65°F, 70°F and 160°F fluid/ambient temperatures.

Task 6 - Component Fabrication and Qualification Test: Unique components for the FHBS, designed within Task 8, were fabricated and flight qualified under this task. The reservoir/separator parts and several special fittings were manufactured by Aircraft Standards of Seattle, Washington. Boeing manufactured, modified and assembled the remainder of the new components. Testing was conducted per the test plan (Appendix B) generated in Task 5, and the results reported in the Task 8 - Class II Modification Document (Part II), Reference 8, and Section VIII of this report.

Task 7 - System Test and Simulation: A laboratory test rig mockup of the KC-135 FHBS, designed within Task 8, was prepared to conduct performance and flightworthiness testing. The test rig was placed in an environmental chamber for high and low temperature testing. System and simulator testing was conducted per the system test plan (Appendix C) generated in Task 5, and reported in Task 8 - Class II Modification Document (Part II), Reference 8, and Section IX and Appendix D of this report.

Task 8 - Class II Modification Documentation (Part II), Reference 8: This task developed the final FHBS design, analysis and documentation. The Task 3 - Part I preliminary modification documentation was reworked from layout (preliminary design) drawings into formal released drawings; and from preliminary performance and stress analyses into laboratory test reports and formal stress analyses. A FHBS kit installation procedure for the test airplane was specified, and the maintainability data to fill and bleed air from the CTFE and MIL-H-5606 hydraulic fluid systems and to service the CTFE reservoir were provided. The Part II document contained a statement of FHBS flightworthiness certification.

Task 9 - System Hazard Analysis: The Task 4 Preliminary Hazard Analysis was utilized in the development of the Subsystem/System Hazard Analysis (Reference 6) and the Operating and Support Hazard Analysis (Reference 7) for Task 9 by the C/KC-135 Program organization. These analyses aided the development of the FHBS design (Task 8) by determining the system's potential safety problem areas.

Task 10 - Flight Test Demonstration Procedure: A recommended aircraft test program was specified in the Flight Test Demonstration Procedure for the FHBS. The procedure detailed the minimum, as well as suggested, instrumentation and testing required to perform a test program on a demonstrator FHBS. The data derived from the test instrumentation was intended to determine actual aircraft braking performance equivalence.

Task 11 - Reliability/Maintainability Analysis: The Integrated Logistics Support (ILS) organization performed a preliminary reliability/maintainability analysis of the candidate FHBS CTFE fluid replenishment schemes developed in Task 1, and an analysis of the final FHBS design for Task 8. These analyses included the failure rates, maintenance task frequency and maintenance man-hour requirements. Also, ground service equipment and possible/probable servicing errors were reviewed with recommendations for the Task 8 final FHBS design and the Task 7 systems servicing tests.

III. FIREPROOF HYDRAULIC BRAKE SYSTEM DEVELOPMENT

The C/KC-135 was selected as the study aircraft as its brake system is representative of a modern large aircraft brake control system. A schematic of the C/KC-135 main gear wheel brake system is shown in Figure 2. The aircraft has two four-wheel-type main landing gears with paired wheel brake control. That is, the brake pressure associated with the forward and aft wheel pair on one side of the truck is controlled by a single antiskid valve and antiskid electronic control system.

1. DEVELOPMENT AND ANALYSIS OF REPLENISHMENT SYSTEM CONCEPTS

The development of a two-fluid brake system design utilized, as a baseline, the system presented in the prior contract's final report (Reference 2).

The Reference 2 proposed (baseline) FHBS, shown in Figures 3 and 4, utilized a modified design of the brake deboost valve as the two-fluid separator. The proposed modifications to the C/KC-135 brake system deboost valve included replacing the existing replenishment valve in the piston with a plug, redesigning the end cap to delete the replenishment valve actuating pin, and incorporating a standpipe and a port for a CTFE replenishment valve. The CTFE replenishment valve design was a mechanically actuated check valve. A high pressure piston type accumulator was the CTFE reservoir.

The existing C/KC-135 brake system utilizes hydraulic fuses as shown in Figure 2 to prevent the draining of a main hydraulic system in the event of large leakage failure in the brake system plumbing or components. Also, as the MIL-H-5606 hydraulic fluid is extremely flammable, the fuse limits the amount of leakage in the vicinity of the brake disk stacks which after normal use are a potential ignition source.

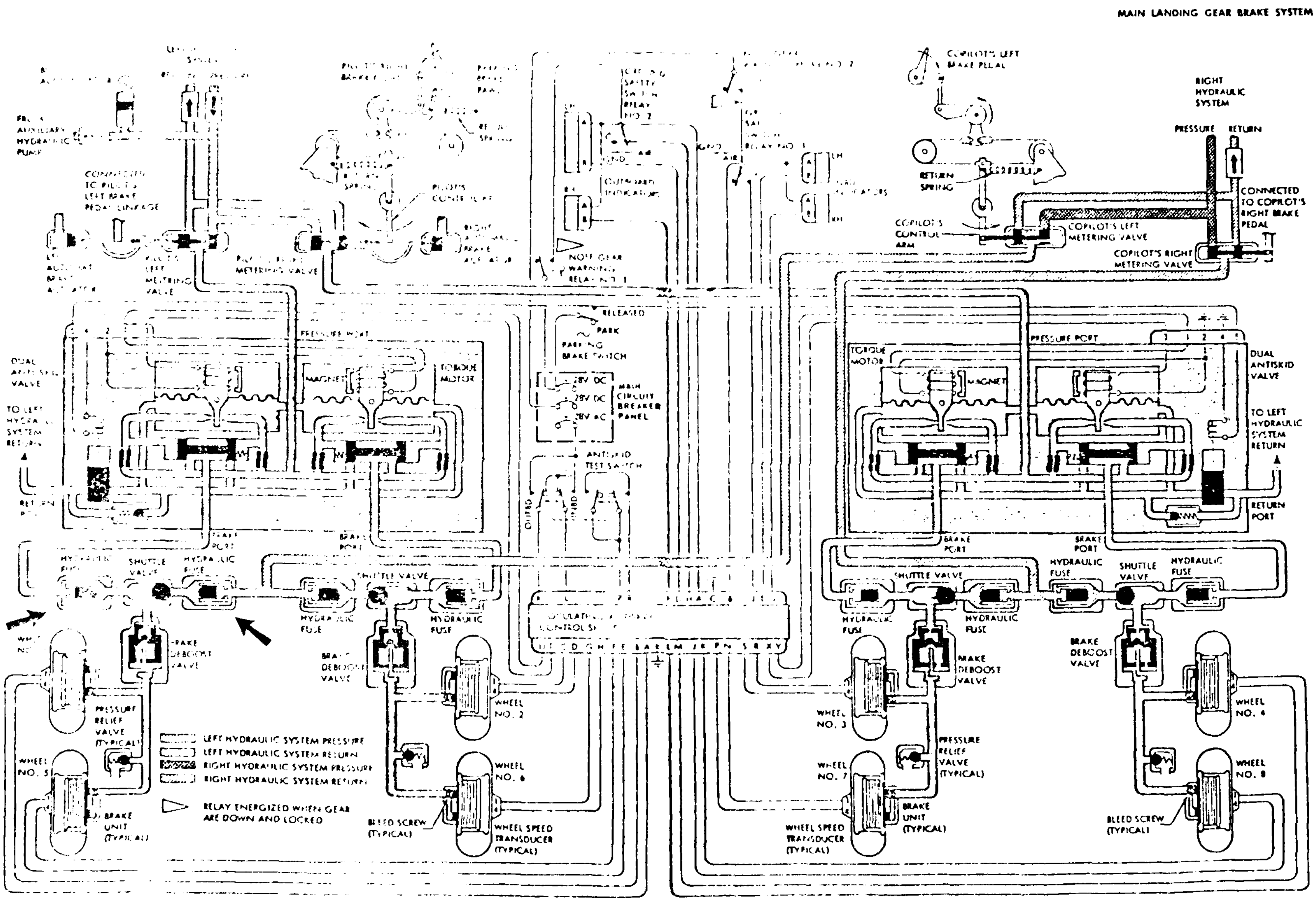


Figure 2. "As-Built"-135 Aircraft Brake System Fuse Locations

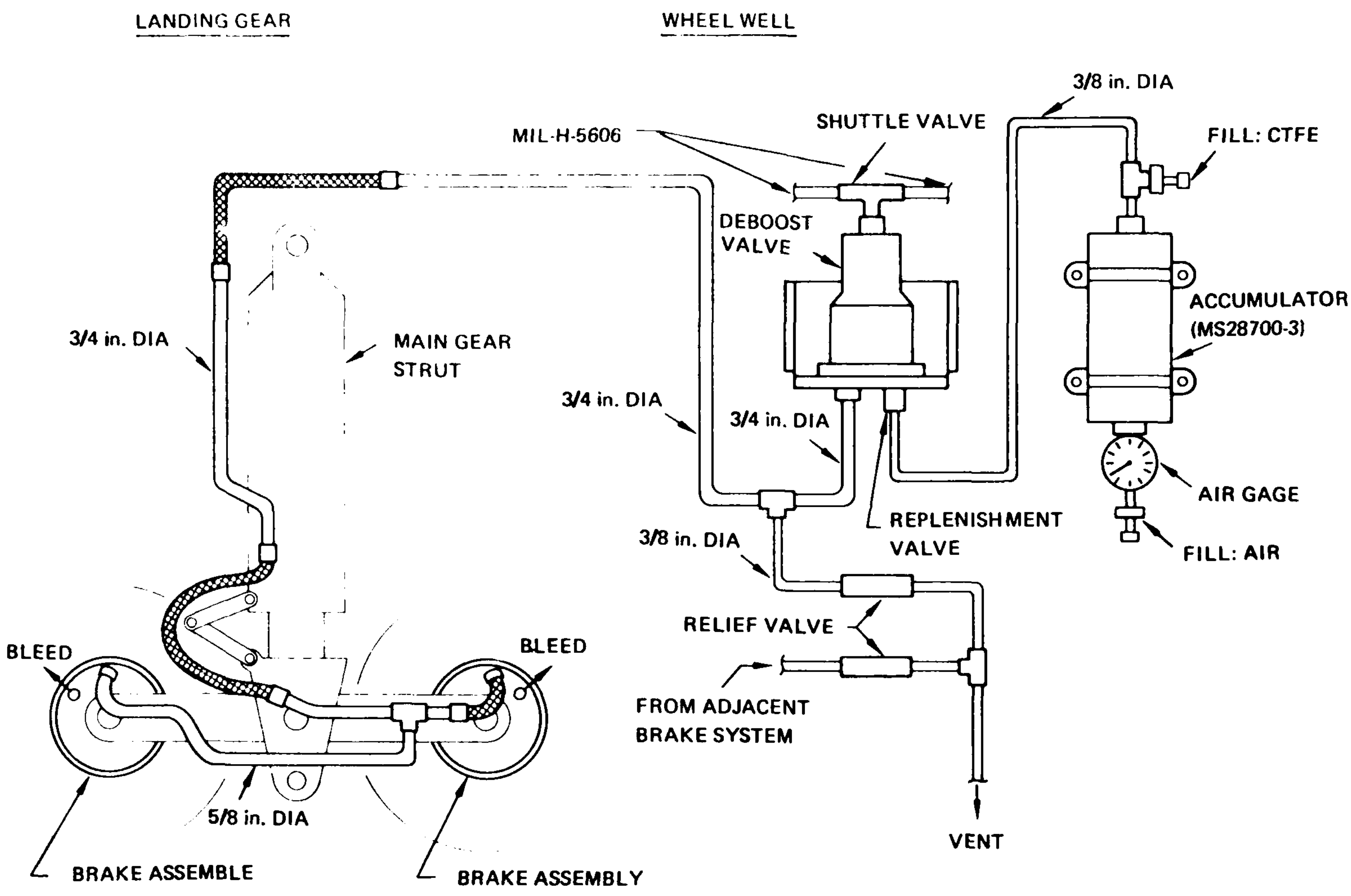


Figure 3. Proposed (Baseline) FHBS

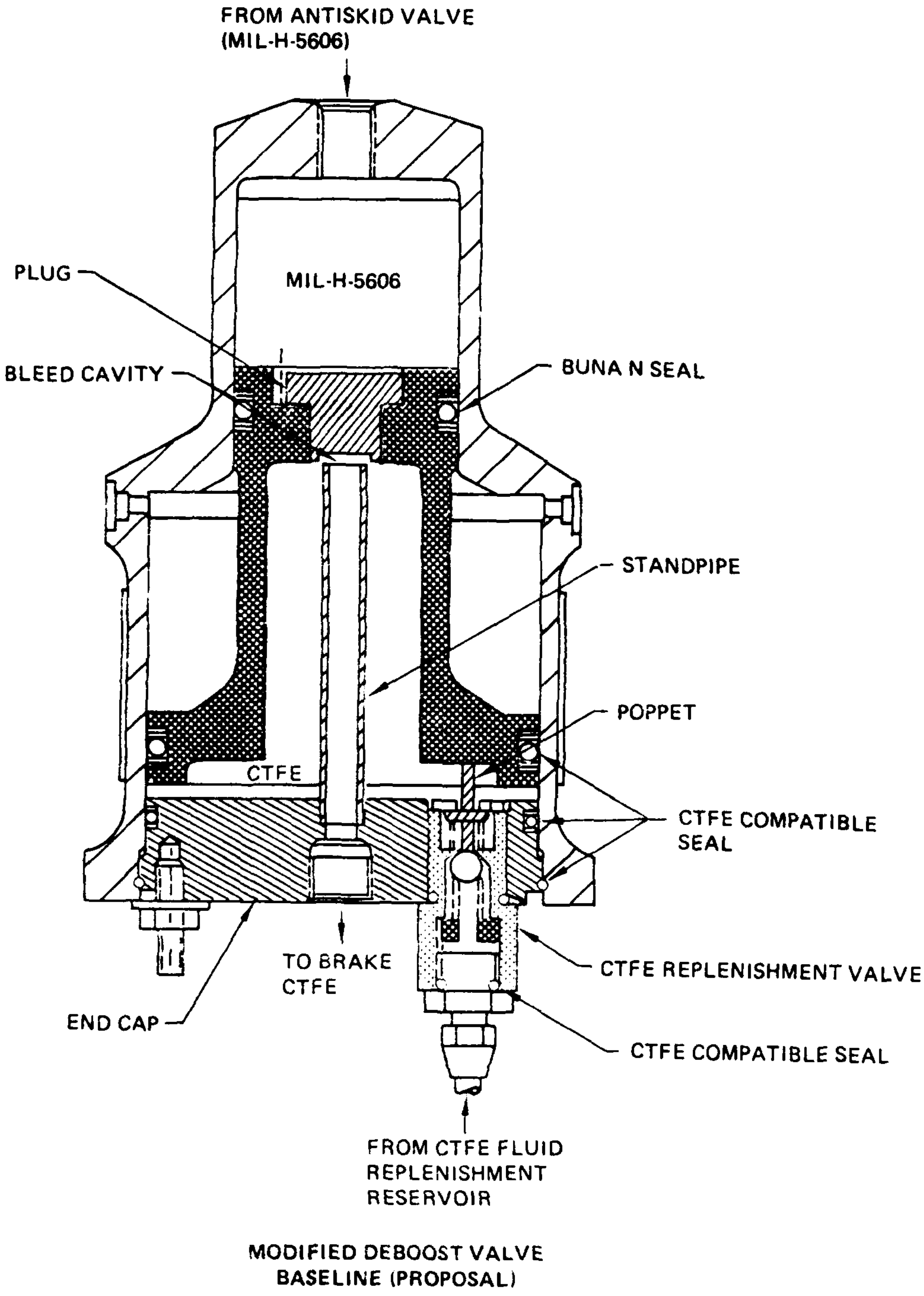


Figure 4. Modified Deboost Valve for FHBS Baseline

The FHBS, by virtue of its use of a fluid separator and a nonflammable hydraulic fluid, contains both design features discussed above, therefore the hydraulic fuses were deleted. Should fluid leakage occur in the CTFE fluid system, the main (MIL-H-5606) hydraulic system is protected by the fluid separator which bottoms when the CTFE system fluid is depleted, and because of its nonflammability, the CTFE fluid poses no fire/safety hazard if it contacts hot brakes.

The Task 1 alternative CTFE replenishment system concepts trade study was initiated using the proposed "baseline" system to which alternative concepts were compared. The "baseline" concept was evaluated for performance similarity to the existing brake system and several differences were identified. The existing system deboost valve piston will travel to the highest position when there is no braking activity and thus start from that position whenever braking is initiated. The "baseline" system deboost valve piston would typically operate at the lower end of stroke, where, at peak brake pressures, the piston will be actuating the replenishment valve. The resulting performance during antiskid braking would be unpredictable and sufficiently different than the existing brake system as to make stopping performance equivalency difficult, if not impossible, to show.

Another problem area was in the air bleeding capability of the "baseline" concept. The existing C/KC-135 brake system deboost valve is self bleeding with all air pockets travelling upward through the replenishment valve and out of the deboost through the upper high pressure port. In the "baseline" concept, the piston plug added to separate the two hydraulic fluids prevents the upward progress of air. The standpipe added to the "baseline" design is used to provide a path for air to travel down and out a bleed valve provided near the bottom of the deboost valve. Bleeding air from the deboost valve would require pressurizing one of the aircraft main hydraulic systems and

pushing on the brake pedals while the deboost bleed valve is opened. When the deboost valve bottoms, the bleed valve is closed and brakes released. This procedure requires a sufficient flow rate to drive the bubbles downward faster than they will rise in the hydraulic fluid. Since at higher temperatures the CTFE fluid has a low viscosity, the flow rate required to bleed air from the system would be fairly substantial. The standpipe tube diameter may be reduced to increase the fluid/air velocity but the reduced diameter would cause an increased pressure drop during dynamic applications of brake pressure/flow as happens during antiskid activity. Thus a conflicting design requirement exists for the standpipe diameter.

An alternative deboost design was devised to minimize the deleterious pressure loss effect of a small diameter standpipe. This design, designated Alternate 1 (Figure 5), provided a large diameter port for brake pressure and a small diameter standpipe for better CTFE system bleeding.

Another concern was the "baseline" concept's potential for locking the brakes. This condition exists for a leaking replenishment valve as well as several valve failure modes (i.e., broken spring, stuck valve, etc.). The resulting safety problem from a single failure makes the "baseline" and Alternate 1 concepts unacceptable.

The "baseline" concept's requirement for a continuous high pressure reservoir causes the potential locked brake problem. Two schemes that reduce the locked brake probability utilize a reservoir that is pressurized only when the brakes are applied. These schemes, Reservoir Alternatives A and B (Figures 6 and 7) require additional system interfaces and a shuttle valve as shown in Figure 8. The two new interfaces provide metered brake pressure from upstream of the antiskid valve or from the co-pilots manual brake system. To reduce the effect of the CTFE reservoir's compliance upon antiskid performance, two restrictors were added to the interface lines.

Reservoir Alternative A (Figure 6) constituted an all new component design that positively prevented the dynamic seal leakage of one hydraulic fluid type

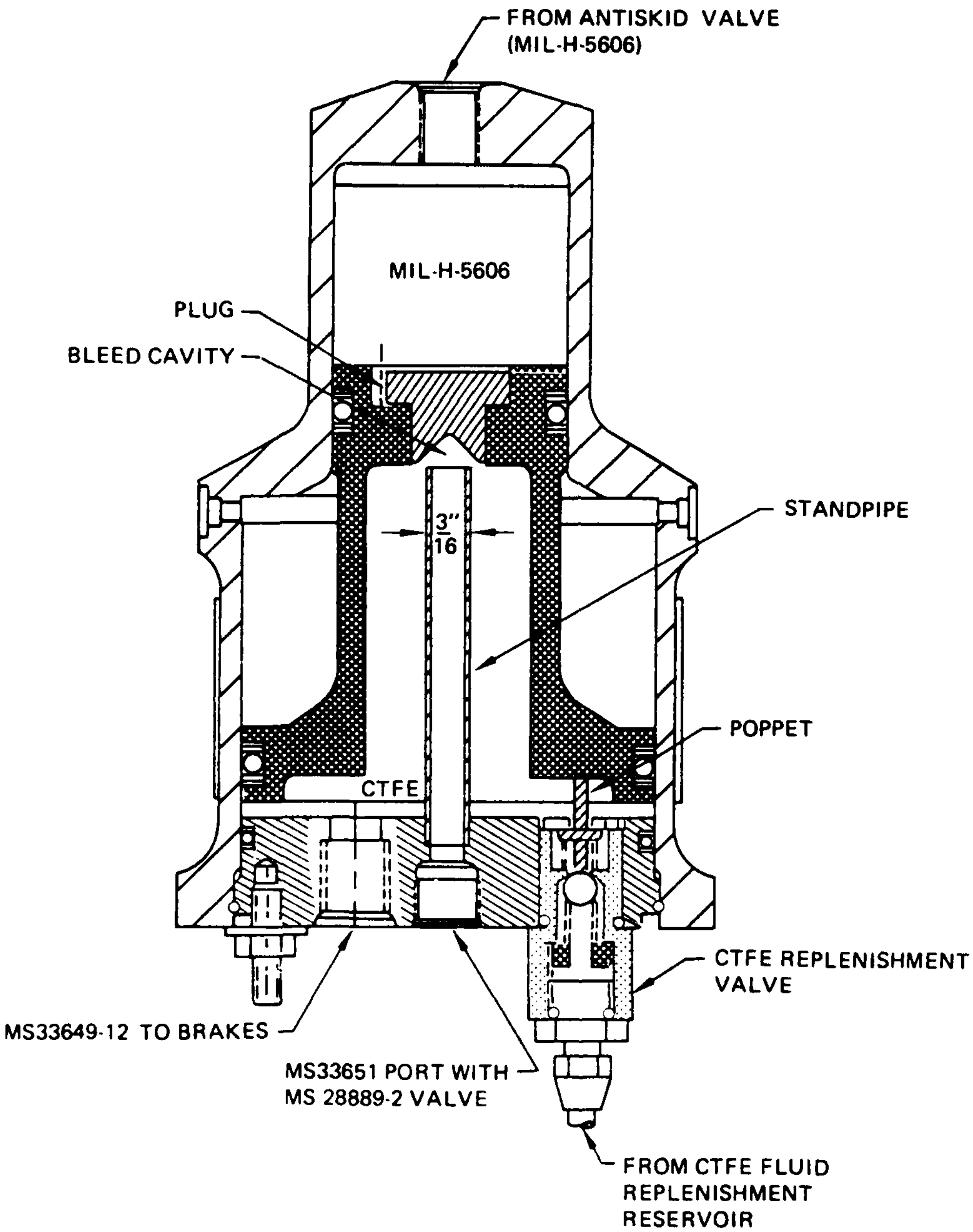


Figure 5. FHBS Alternate 1 Concept

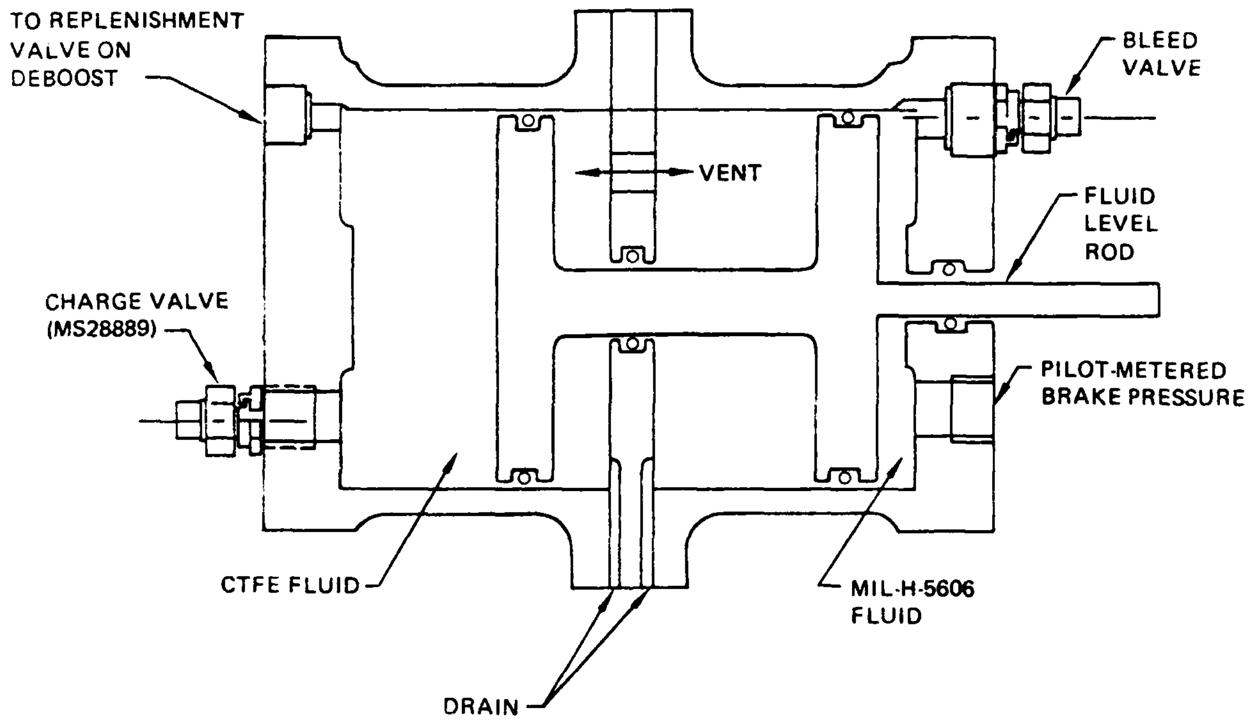


Figure 6. FHBS Reservoir Alternate "A"

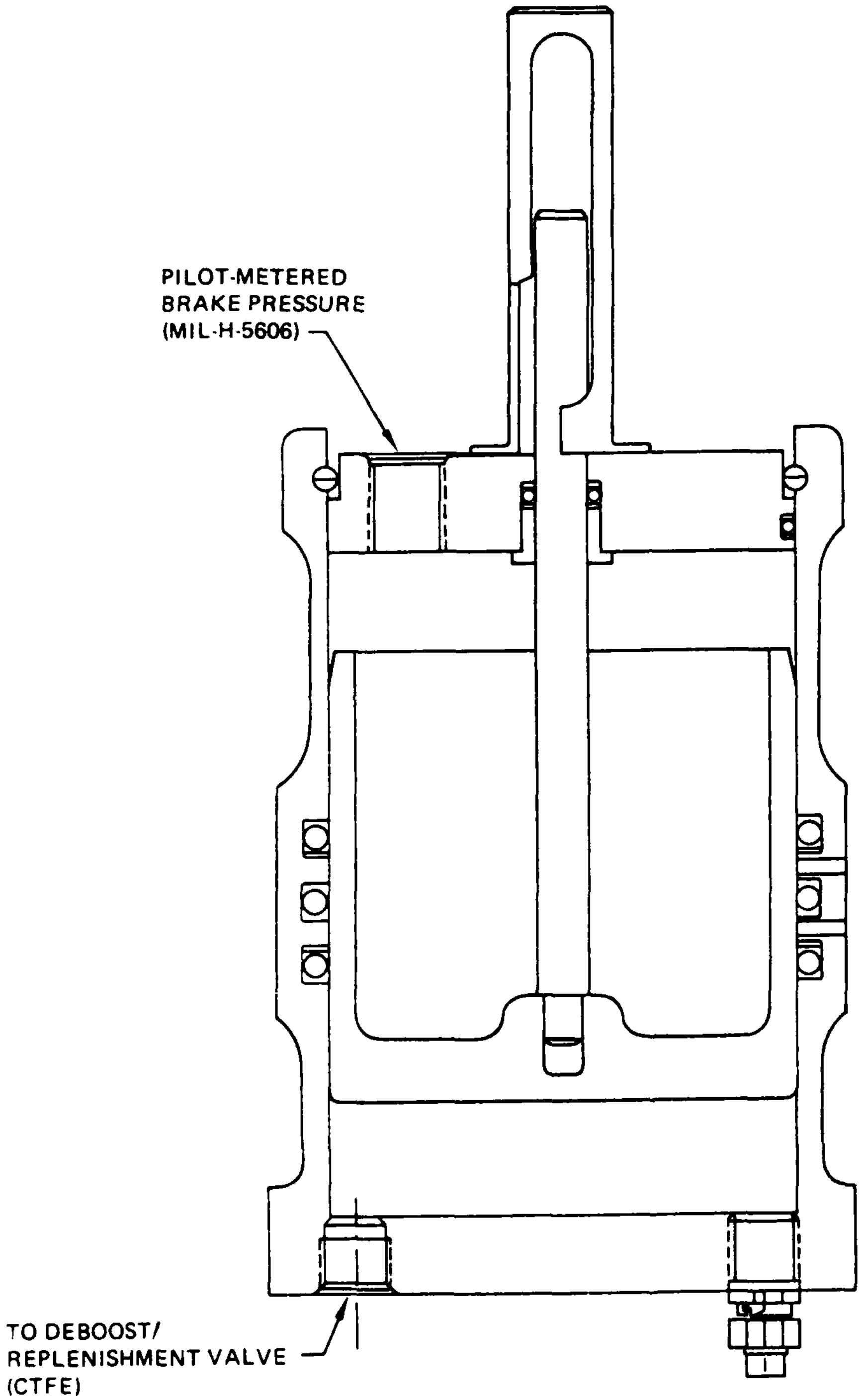


Figure 7. FHBS Reservoir Alternate "B"

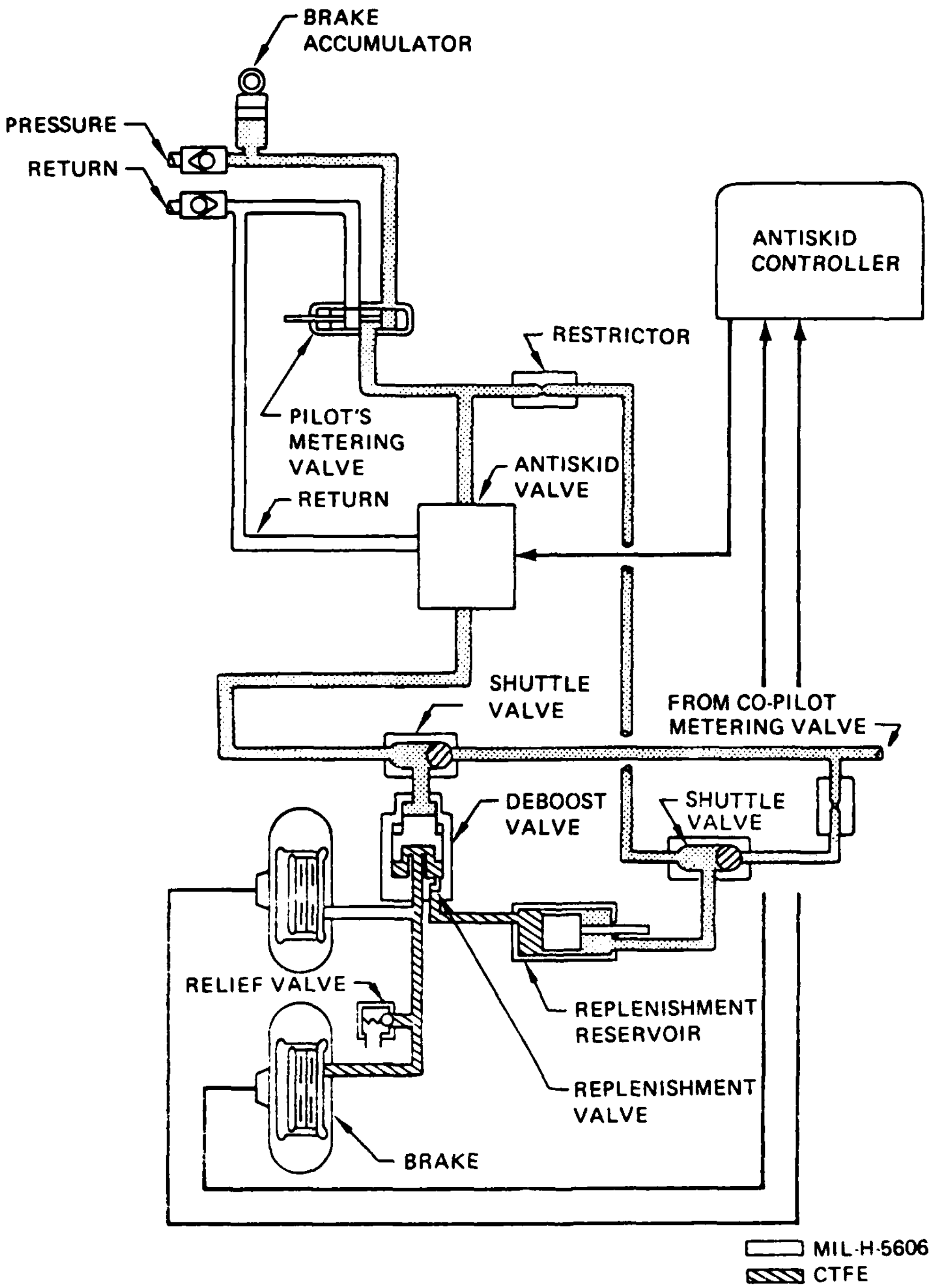


Figure 8. System Schematic For Reservoir Alternates "A" and "B"

from contacting the dynamic seal for the other fluid. This fluid separation design exceeds what could be accomplished in the "baseline" deboost valve. A rod protruding from the reservoir gives an accurate indication of the CTFE fluid level which is not attainable with the "baseline" concept. However, the multiple concentric diameters constitute a difficult and expensive design to manufacture.

The shortcomings of the Alternate A design were examined and resulted in the several design improvements of Reservoir Alternate B concept shown in Figure 7. In this design, while the positive separation of leakage fluid(s) is retained, the multiple concentric diameters are minimized thus significantly lowering the manufacturing expense.

Another method of avoiding the "baseline" concepts' locked brake failure mode is to use a low or non-pressurized CTFE reservoir. Alternates 2, 3, and 4 were devised utilizing this method.

Alternate 2 (Figure 9) retains the deboost valve as a fluid separator with the piston plug but requires a major change to the end cap design. This concept uses a spring loaded piston which during periods of nonbraking returns the piston to a position that has sufficient displacement to apply brakes for worn disks and/or stators. The design incorporates a piston unloading scheme that removes the spring force on the piston for the upper 0.4 inch of stroke. This upper-displacement is intended to take care of the CTFE thermal expansion that may occur during the soak-back of post-landing, pre-takeoff taxiing or environmental temperature increase. The deboost piston will operate from the top of stroke thus giving a higher degree of performance similarity to the existing system.

The Alternative 2 system used a free-return flow type relief valve between the unpressurized reservoir and the brake line as the CTFE replenishment valve. The relief valve would prevent pressures in excess of 1000 psi in the lower brake system (downstream of the deboost) for several failure modes. The free return allows makeup fluid flow from the reservoir into the lower brake

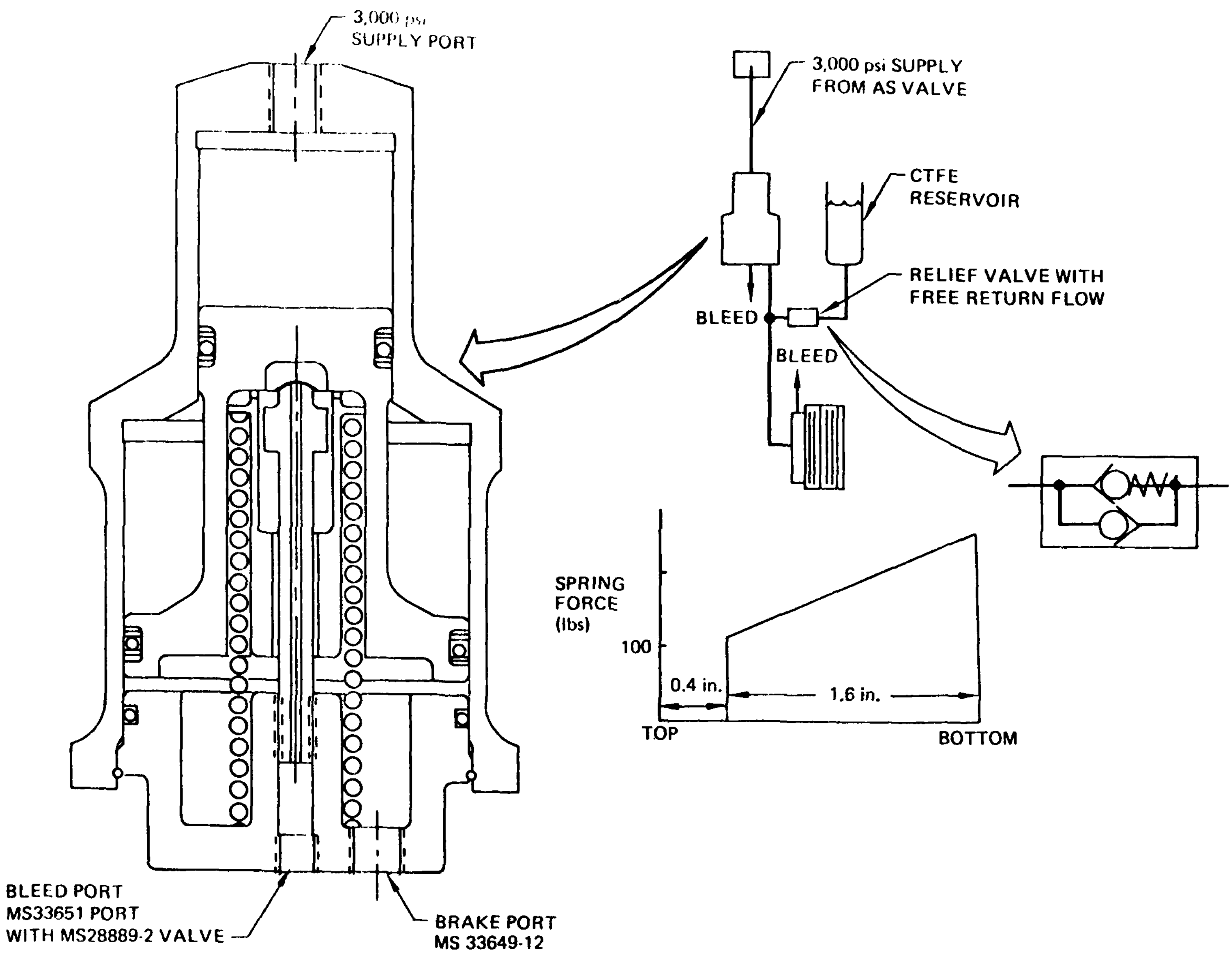


Figure 9. Alternate 2 Concept for FHBS

system. The unpressurized reservoir is lightweight and requires no additional brake system interfaces. The CTFE fluid level would be determined from a sight gage adjacent to the reservoir. The spring in this design is expected to generate high levels of contamination due to contact with the piston inside diameter and the spring inside diameter guides. Assembly and disassembly of the spring loaded deboost valve was considered to be unsafe without special holding fixtures that prevent rapid release of the spring's stored energy.

Alternate 3 (Figure 10) design concept deleted the spring loaded piston while retaining the use of a low pressure reservoir to prevent the "baseline's" locked brake safety problem. This concept has the deboost piston actuating a valve only when the CTFE fluid flows back to the reservoir. The valve is spring loaded onto a seat to seal off the reservoir fluid. When the upward moving piston reaches 0.1 inch from full up position, a tang mechanism is raised by contacting the piston's catch plate to lift the valve from its seat, allowing fluid passage between the deboost lower end volume and the reservoir.

The reservoir for Alternate 3 required pressurization to a level above a third of normal reservoir pressure but less than the brake retract spring capability. The minimum reservoir pressure must overcome deboost piston seal friction. The maximum reservoir pressure must be reduced to account for brake piston and deboost piston seal friction to prevent dragging brakes. The required CTFE reservoir pressurization system is presented in Figure 11.

The high number of intricate parts in the Alternate 3 deboost valve reduced reliability and serviceability ratings. The additional interface required to pressurize the reservoir tended to reduce reliability and maintainability, while increasing the time and cost to demodify the aircraft.

Alternate 4 (Figure 12) retained the advantages of Alternate 3 while simplifying the design and improving the bleeding capability. This design used an internal replenishment valve that integrated the bleeding function. The bleeding was accomplished when the deboost piston was at the top of stroke therefore decreasing the amount of CTFE fluid lost during the bleeding

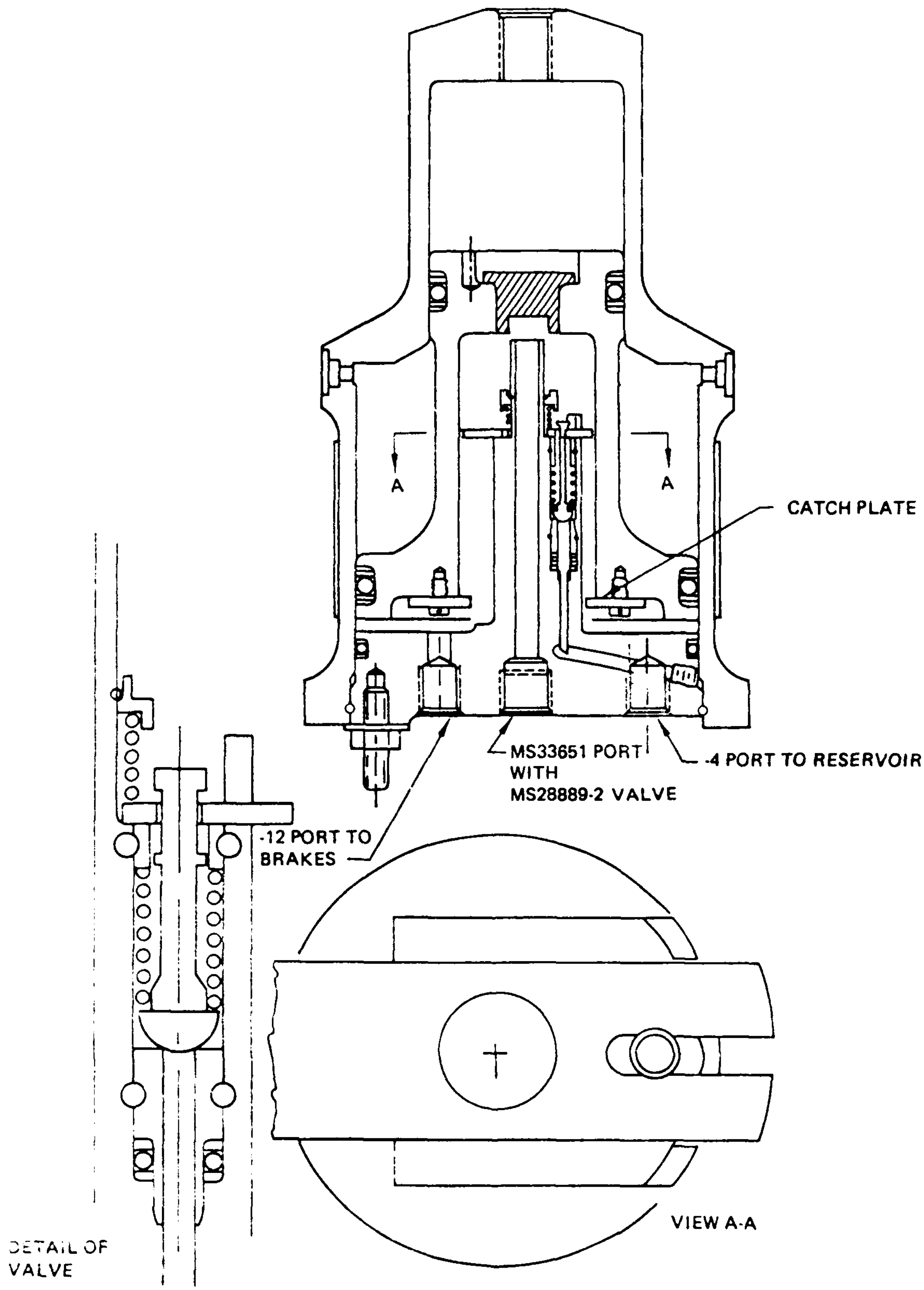


Figure 10. Alternate 3 Concept for FHBS

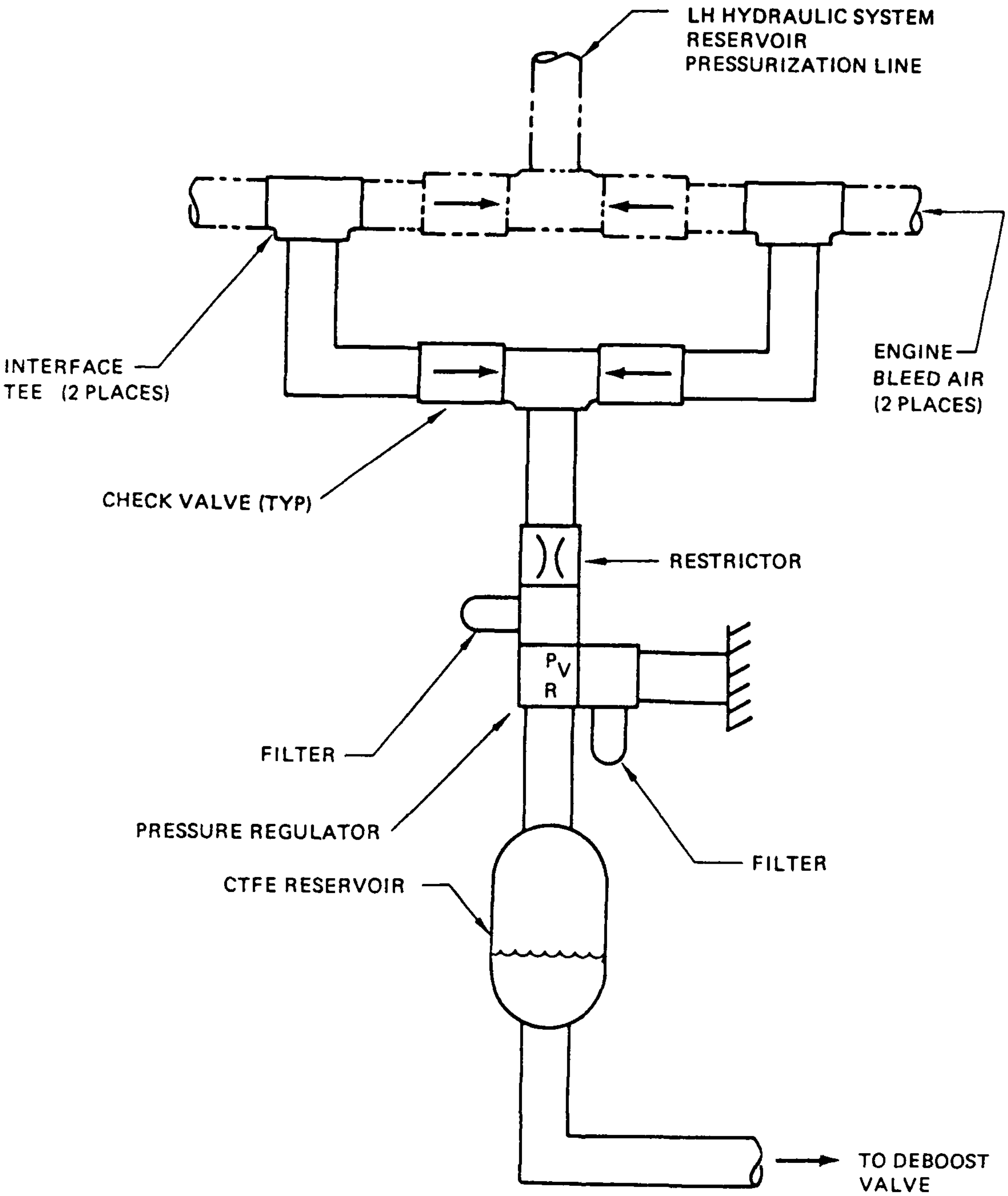


Figure 11. CTFE Reservoir Pressurization System for Alternates 3 and 4

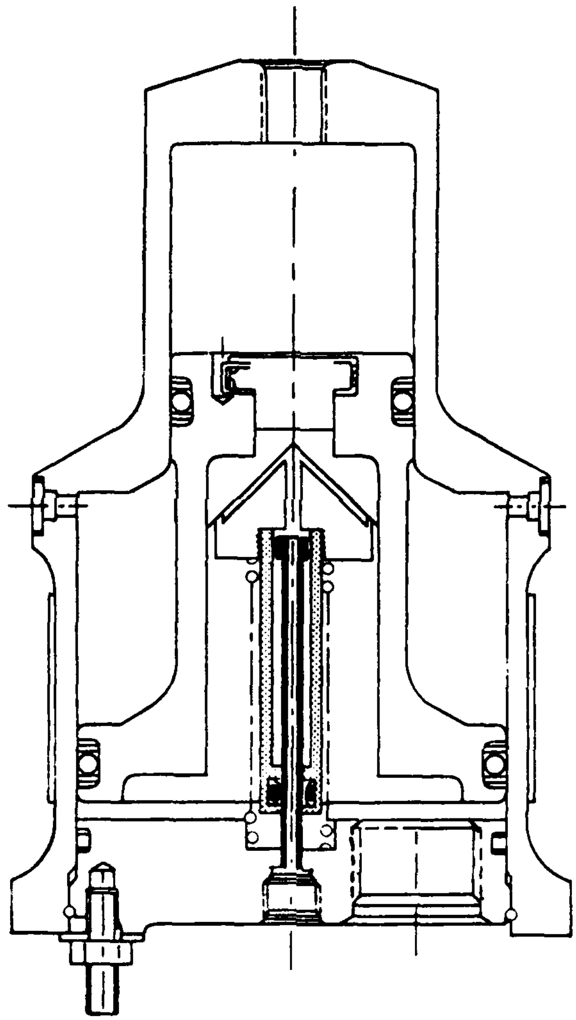


Figure 12. Alternate 4 Concept for FHBS

procedure. The design used the area difference of the poppet seal minus the stem seal and the pressure differential of the reservoir and the lower deboost valve to balance the spring force and achieve the sealing when no additional fluid is required from the CTFE reservoir. For CTFE fluid thermal expansion, the expanding fluid raises the deboost piston to a point 0.1 inch from the top of stroke where the poppet guide contacts the port cap stem allowing the excess CTFE fluid to return to the reservoir. This process also gives this concept some degree of self bleeding.

Bleeding of the Alternate 4 system would be accomplished by pumping CTFE fluid into the brake line fill valve causing the deboost piston to rise until the poppet seal opens. Air and fluid are then forced down the poppet guide and stem to a bleed valve or back to the reservoir.

The reservoir configuration for Alternate 4 required a pressurization system (Figure 11) similar to Alternate 3, therefore, retaining those negative features of additional interfaces.

The evolution of the previously described alternate concepts, show that designing to achieve a near constant minimum force with the spring while retaining a tight seal of the poppet against the piston during antiskid pressure cycling, all complicated by variations in the stem seal friction, was a design challenge.

Alternate 5 (Figure 13) was a scheme devised to avoid several of the inherent problems caused by using the deboost valve as the fluid separator. Very small quantities of air in a brake fluid system can cause significant loss of antiskid braking performance. The deboost valve, when designed with the piston plug to achieve fluid separation, has a large air trap that heavily compromises the design. The Alternate 5 system eliminated this problem by using the deboost "as-is" totally within the CTFE fluid system and providing for fluid separation in a new component referred to as a reservoir/separator.

The reservoir/separator is of simple design similar to many hydraulic actuators. A concern for this type of design was the piston inertia effect on

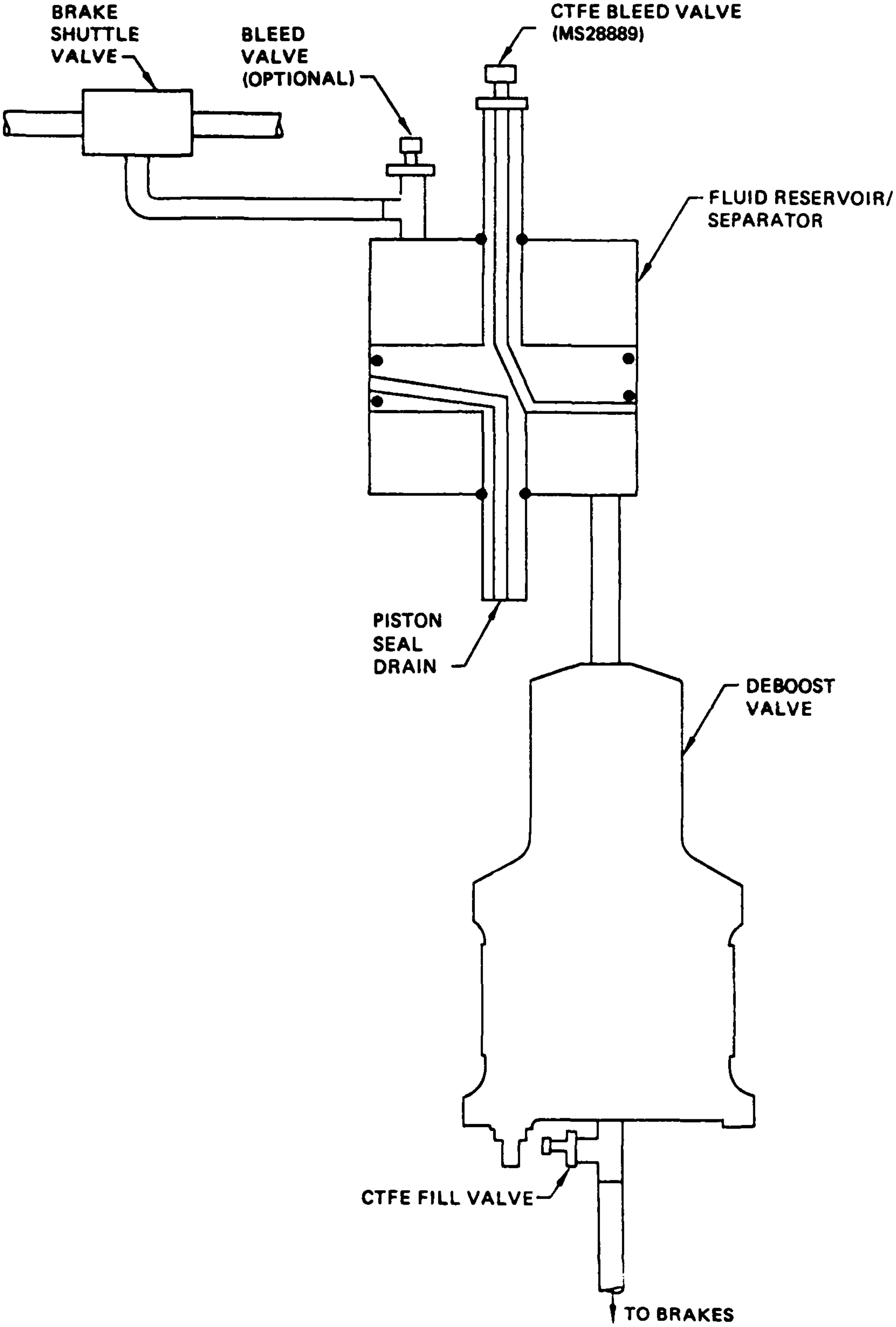


Figure 13. Initial Alternate 5 Concept for FHBS

reducing antiskid performance. The piston inertia problem was minimized by using as large a diameter as possible. This can be seen when noting that for a given fluid volume, required by the brake during an antiskid cycle, the maximum piston velocity is reduced by the square of the piston diameter. Mass of the piston, while increasing by the square of diameter per inch of stroke, is also reduced by the shortening stroke length. Since inertia is affected by the square of the velocity, but only the first power of mass ($I=mv^2/2$), the reduced inertia effect with increasing diameter is obvious.

The location of the reservoir/separator upstream of the deboost valve was also done for effective inertia considerations. Downstream of the deboost valve, the flow rates are trebled because of the three-to-one area ratio. Therefore, the increase in effective piston inertia would be nine-fold. Seal friction would also have a greater effect upon dynamic performance.

The first Alternate 5 reservoir/separator concept was to use an "area balanced" actuator design with a rod extending from both ends of the housing. This concept would use two seals on the piston, one for each fluid type with seal leakage exiting through the lower rod. The upper rod was required to bleed air from the CTFE system and was used as the CTFE fluid volume indicator. A design requirement that would not allow the Buna-N (MIL-H-5606 fluid) seal to pass over a part of the housing that had contained the CTFE fluid combined with minimizing the moving mass, increased the size, design and manufacturing complexity to a point of excessive cost.

The next Alternate 5 reservoir/separator design scheme (Figure 14) eliminated the lower piston rod that was used as the CTFE/MIL-H-5606 piston seal leakage passage. The design was area unbalanced but, with the selected rod and piston diameters, amounted to only a 2.8% decrease in MIL-H-5606 fluid pressure from the CTFE fluid pressure. The piston seals were designed into the housing and the leakage path provided as weep holes in the housing between the seals.

The Figure 14 Reservoir/Separator Layout incorporated a MS28889-2 valve on the piston rod to bleed air from the CTFE system. This valve allowed a clear

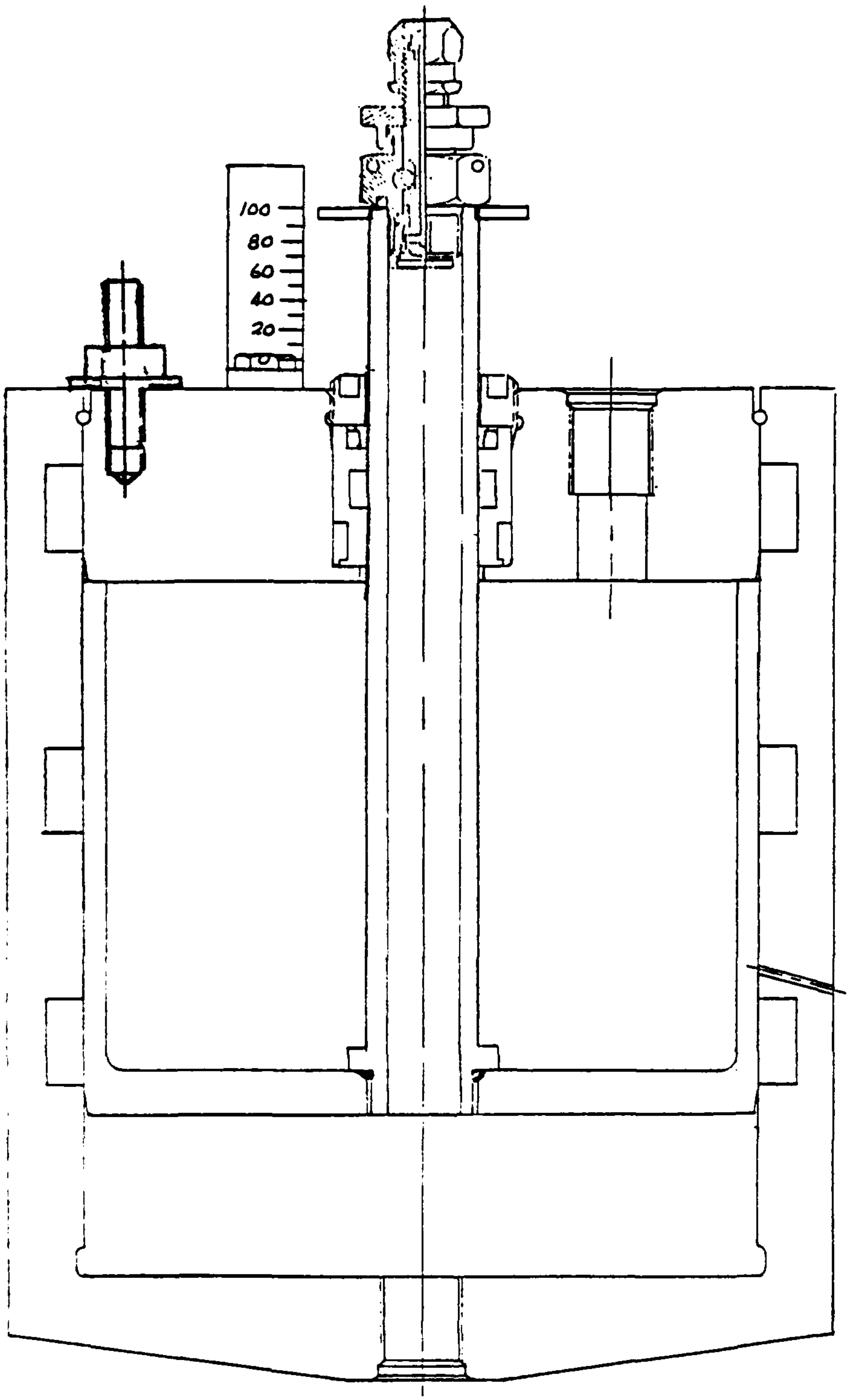


Figure 14. Preliminary Design Layout of Reservoir/Separator

plastic hose to be attached such that fluid/air bled from the system could be caught for easy disposal.

Study of the large diameter piston seal friction changed the seal system selection from an elastomeric O-ring with an uncut loaded TFE backup ring on each side to a spring energized plastic ring design.

An end cap trapped ring retainer design, similar to that on the deboost valve, was inadequate for the higher pressure design. A design utilized on the Boeing 757 aircraft nose gear retraction actuator was used to provide increased strength in the redesign of the retainer on the FHBS reservoir/separator.

Installation of the reservoir/separator, when stacked with the deboost valve, required relocating it from the original deboost valve location to the aft outboard corner of the wheel well. Stacking the two components reduced the bleeding maintenance task when compared to two separated units. Detail layouts of the installation brackets for the stacked units were significantly less complex if the units were tilted 5^{o} (top inboard). The reservoir/separator piston exterior bottom was conically shaped to allow air in the CTFE fluid to float up to the bleed valve. The tilt also reduced the amount of trapped air volume on the MIL-H-5606 fluid side of the piston. The reservoir/separator redesign resulted in the Figure 15 layout.

Also noted on the plumbing installation layout was an air trap at a high point in the CTFE fluid line between the deboost valve and the brakes. At the high point, a tee and bleeder plug were added to allow more effective bleeding of the CTFE fluid system.

2. ANALYSIS OF CONCEPTS

a. Reliability/Maintainability Analysis--A review of the FHBS "baseline" and alternate concepts was conducted by the Integrated Logistics Support (ILS) group. The ILS review covered the areas of reliability,

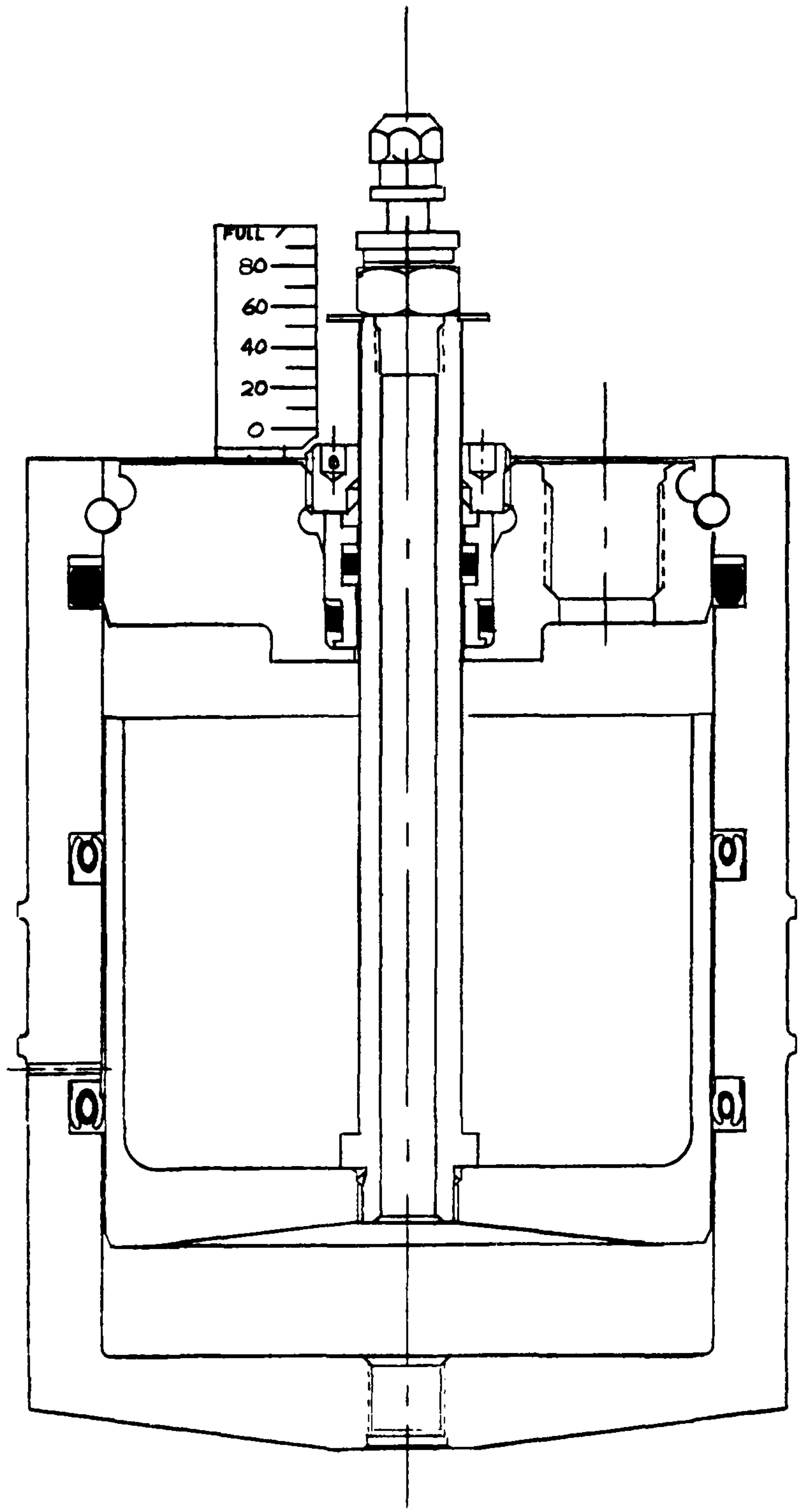


Figure 15. FHBS Reservoir/Separator Final Design

maintainability, and serviceability on each concept. Table 1 summarizes the results of the ILS study. The "score card" grades (Table 2) for the evaluation criteria, reliability, maintainability, and serviceability, reflect the relative numerical data expressed in Table 1. For example, the reliability grade ratio for the "baseline" and Alternate 5 was 5/7 which reflected the failure rate (λ /1000) (failures per 1000 flight hours) of 2.031/1.45 as shown in the study.

Another consideration evaluated was the effect of deleting the two hydraulic fuses used in the existing C/KC-135 brake system. Each fuse had a failure rate of .093 per 1000 flight hours and a repair rate of .00015 maintenance manhours per flight hour.

A safety review of the concepts determined that the "baseline" and Alternate 1, which use the pressurized accumulators as a reservoir, were likely to cause locked brakes and therefore, were unsafe. When the "baseline" and Alternate 1 concepts deboost valves were combined with reservoir Alternate A or B, the locked brake problem was diminished but the additional system complexity and/or interfaces tended to reduce some of the advantages. Alternates 2 through 5 concepts were significant safety improvements over the "baseline" because of the minimal possibility of locked brakes. These concepts have individual safety related differences in that certain failure modes could have caused the loss of braking on the test wheel pair. Since a particular failure is more likely to occur than another, a concept will have a higher or lower safety score than another.

b. Brake Performance Analysis--A hydraulic system frequency response analysis of the FHBS "baseline" and candidate design concepts was accomplished. The details of this analysis, previously reported in the Interim Report, Reference 5, are included herein as Appendix A.

The objectives of this frequency response analysis were: (1) to predict the frequency response of the candidate system designs and compare the results with the predicted response of the "as-built" C/KC-135 Mark II antiskid, five

Table 1. Reliability/ Maintainability Study Data

	λ/1000	MTTR	MMHR/TASK	MMH/FLT HR	EST. EASE OF SERVICE	OVERALL REC. RATE
BASELINE	2.03	1.7	6.81	.0138	4	6
BASELINE/ALT A	1.64	3.22	3.47	.0057	4	6
BASELINE/ALT B	1.64	3.22	3.47	.0057	4	6
ALT 1	2.03	1.7	6.81	.0138	3	5
ALT 1/A	1.64	3.22	3.47	.0057	3	2
ALT 1/B	1.64	3.22	3.47	.0057	3	2
ALT 2	1.29	1.69	3.52	.0045	2	2
ALT 3	1.50	1.74	3.63	.0054	2	4
ALT 4	1.32	1.69	3.5	.0046	2	3
ALT 5	1.45	1.53	3.1	.0045	1	1

λ/1000 = FAILURES PER 1000 FLIGHT HOURS
MTTR = MEAN TIME TO REPAIR (AIRCRAFT)
MMHR/TASK = MAINTENANCE MAN HOURS PER TASK
MMH/FLT HR = MAINTENANCE MAN HOURS PER FLIGHT HOUR

Evaluation criteria	Multiplier	Baseline (proposal configuration)		Baseline/ Alternate A or B Reservoir		Alternate 1		Alternate 1/ Alternate A or B Reservoir		Alternate 2		Alternate 3		Alternate 4		Alternate 5	
		Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score
Weight	2	5	10	4	8	5	10	4	8	7	14	5	10	5	10	3	6
Cost	5	5	25	3	15	5	25	3	15	4	20	3	15	4	20	6	30
Reliability [1]	7	5	35	6	42	5	35	6	42	8	56	7	49	8	56	7	49
Maintainability [2]	7	3	21	5	35	4	28	6	42	9	63	8	56	9	63	10	70
Serviceability [3]	5	4	20	8	40	4	20	8	40	8	40	7	35	8	40	9	45
Safety [4]	10	2	20	7	70	2	20	7	70	7	70	6	60	8	80	9	90
Installation	5	8	40	6	30	8	40	6	30	7	35	7	35	7	35	5	25
Developmental risk [4]	8	9	72	8	64	9	72	8	64	7	56	6	48	8	64	10	80
Dynamic performance [4]	9	3	27	3	27	4	36	4	36	7	63	9	81	9	8[illegible]	8	72
Mixed fluid potential	8	8	64	7	56	8	64	7	56	5	40	8	64	8	64	9	72
Reinstallation time and cost	4	8	32	5	20	8	32	5	20	8	32	6	24	6	24	5	20
Total score			366		407		382		423		489		477		537		559

[1] Grades based upon $\lambda/1{,}000$ (failures per 1,000 flt-hr) data from task 11, "Reliability/Maintainability Study."

[2] Grades based upon MMH/flt-hr (maintenance man-hours per flight hour) and estimated ease of service data from task 11, "Reliability/Maintainability Study."

[3] Grades based upon MMH/task (maintenance man-hours per task) data from task 11, "Reliability/Maintainability Study."

[4] Grades of 5 or higher are acceptable for these critical criteria.

Table 2. FHBS Trade Study Score Card

rotor brake system in regards to brake antiskid performance, and (2) to use the frequency response analytical models during the Task 1-FHBS design phase to evaluate the impact of configuration and fluid property changes on system response.

This study used the USAF-developed Hydraulic System Frequency Response (HSFR) computer program which was previously modified as described in Reference 2. In summary, the modifications to the HSFR program included: (1) addition of a fluid separation piston component; e.g., deboost valve piston, (2) addition of a brake model, and (3) providing for two hydraulic fluids in a system. The technique used to develop analytic models of the brake hydraulic system was verified using frequency response test data obtained during the previous program and reported in Reference 2.

The results of this study indicated that the two-fluid brake hydraulic system can have frequency response characteristics very nearly equal to the predicted "as-built" C/KC-135 Mark II brake system characteristics through the first mode (the frequency where 90° phase shift occurs) with the appropriate hardware configuration. The results also predicted the second mode response although the predicted peak gain was greater than anticipated in the actual system. The reason for the large peak gain is that the HSFR analytic model is based on linear system characteristics. The major source of damping in the "as-built" system is the non-linear pressure drop at the deboost valve ports. These minor pressure losses vary as the square of the flowrate, but the HSFR program uses a pressure drop relation that is linearized about a typical flow chosen by the user.

During the course of the evaluation of various FHBS concepts (Task 1), Alternate 5 was left identified as the tentative prime candidate system. In addition, system installation restraints were identified at the design coordination meeting held at BMAC Wichita on October 12, 1983. Therefore, a series of system design concepts for Alternate 5 were examined and compared to the performance objectives for the brake antiskid system. These studies lead to revising the line sizes and to incorporating a one-way restrictor in the

MIL-H-5606 fluid portion of the system downstream of the shuttle valve. The purpose of the one-way restrictor is to add pressure drop, i.e., system damping, during the pressure application portion of the brake antiskid cycle to prevent brake pressure overshoot. Pressure overshoot can cause secondary wheel skids.

The frequency response was also determined for fluid temperatures of $-65^{\circ}F$ and $160^{\circ}F$ for the Alternate 5 and the "as-built" C/KC-135 systems. These data indicated the two-fluid brake system has better frequency response characteristics than the "as-built" C/KC-135 system at $-65^{\circ}F$. The two-fluid system performance at $70^{\circ}F$ and $160^{\circ}F$ for the restricted flow case has a lower first mode frequency by 1.5 Hertz and a lower first mode peak gain by 1.0 db than the "as-built" system.

This analysis concluded that the two-fluid system performance at the extreme and $70^{\circ}F$ fluid temperatures exceeded or equaled the performance of the "as-built" system. Based on the frequency response analysis, it was recommended that system "5D", which incorporates a one-way restrictor in the MIL-H-5606 fluid portion of the system downstream of the shuttle valve, be the prime candidate design for the FHBS.

c. Design, Weight, and Cost Analysis--The design, weight, and cost analyses of the various candidate concepts and baseline design were performed informally through coordination with several organizations which provided comments and data to aid in the trade study grading.

3. TRADE STUDY OF REPLENISHMENT SYSTEM CONCEPTS

a. Trade Study Evaluation Criteria--The replenishment system concept trade study evaluation criteria included a "weighting" by importance of each criteria and a basis for formulating the "weights".

Before attempting a ranking by importance of the criteria, a set of ground rules were established as follows:

- o The FHBS design is for a demonstration flight test program and not intended for a fleet-wide kit.
- o The FHBS design shall be as safe or safer than the existing system.
- o The potential for mixing of hydraulic fluids shall be minimized.
- o The FHBS shall provide equivalent braking performance compared to the existing system.
- o Development risk shall be kept to a minimum.

D. Trade Study Criteria Weighting--Recognizing that some criteria are more important than others, a "weighting" of each was accomplished per the following. The Trade Study Evaluation Criteria were listed in descending order of relative importance and then assigned a multiplier ("weighting") factor (1 to 10) to be used with a configuration grade.

Evaluation Criterion	Multiplier
Safety	10
Dynamic Performance	9
Mixed Fluid Potential	8
Development Risk	8
Reliability	7
Maintainability	7
Serviceability	5
Cost	5
Installation	5
Reinstallation Time/Cost	4
Weight	2

The "weighting" of a criterion was based upon its relative importance to all other criteria. Safety was of prime importance, therefore it was given a "10", while dynamic performance, although being very important, was not rated as important as safety, therefore was given a "9". Likewise, the other criteria were assigned reduced multipliers down to the criteria of weight, which because of its minimal impact on total weight and proximity to the aircraft "cg", was assigned a "2".

The multiplier was used with the configuration's grade to determine a score. The scores for each criteria of a configuration were summed for a total score as shown in the "score card" (Table 2).

c. Trade Study Results--Based on the information in the preceeding sections, Alternate 5 was the tentative concept selection (prime candidate) made for the Frequency Response Analysis (Task 2) and the Preliminary Hazard Analysis (Task 4).

The results of the system response evaluation, performed during the Task 2 frequency response analysis, determined those design changes required to give the prime candidate (Alternate 5) performance equivalency to the existing brake system. As discussed in the final report for the previous contract (Reference 2), increased plumbing diameters will provide improvements in the frequency response performance. However, at several locations along the plumbing routes, physical clearance constraints limited the tube and hose diameter that could be installed. This was especially evident for the hose between the lower wing structure and the main gear strut where the minimum hose bend radius limits the maximum size hose that can be used (since larger hose sizes have greater minimum bend radii). Also a half inch diameter truck tube was the maximum size that could be routed between the truck beam and the strut.

The frequency response analysis also showed a reduction in damping in the higher frequency range which would allow pressure overshoot during reapplication of braking pressure. This problem appeared because of reduced line friction caused by the lower fluid velocities in the larger diameter

plumbing. The pressure overshoot tended to cause secondary skids that reduce the braking effectiveness. This problem is common to many brake system designs and has been eliminated, as in other brake systems, by using a one-way restrictor valve. The valve restricts the hydraulic fluid during pressure application to the brakes by the antiskid valve and allows free flow during pressure removal. The increasing pressure restriction prevents the secondary skids and the decreasing pressure free flow allows the pressure to decay rapidly, therefore removing the tire skid condition. The final system configuration with line sizes is shown in Figure 16.

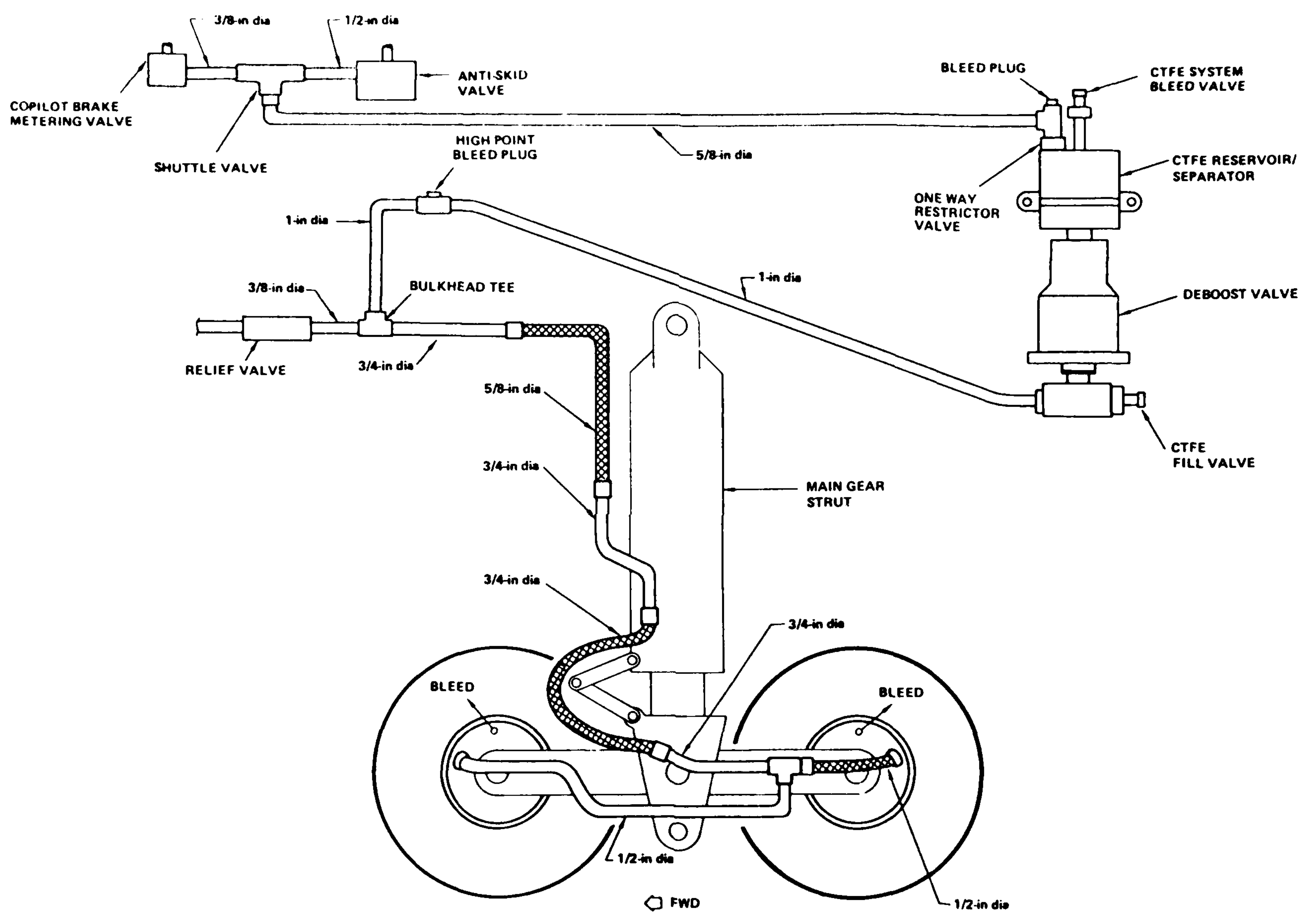


Figure 16. Recommended FHBS Configuration

IV. FHBS DESIGN

The final FHBS design followed the selection of the recommended Alternate 5 concept. The layout drawings and preliminary analyses were formalized for manufacture of the unique FHBS components and for the finalized kit installation drawings.

1. MATERIALS SELECTION

The nonflammable hydraulic fluid used for this contract was formulated and supplied by the Air Force Materials Laboratory (AFWAL/MLBT). The test fluid, designated AO-2, was a chlorotrifluoroethylene (CTFE) oligimer manufactured by the Halocarbon Products Corporation to which a 3M lubricity additive (0.05%) and a barium sulfonate rust inhibitor additive (0.5%) had been added by AFWAL/MLBT personnel. The Materials Laboratory personnel recommended that all new metallic components built or purchased for the CTFE fluid portion of the FHBS be made of stainless steel. It was also recommended that FHBS hydraulic hoses currently using Buna-N rubber as an interior liner be replaced with PTFE lined hoses. The AFML/MLBT elastomer personnel recommended the use of Firestone's Phosphonitrilic Fluoroelastomer (PNF) for elastomeric O-rings in the CTFE fluid system. C.E. Conover, Inc. was the recommended source of modified PNF O-rings (C.E.C. compound designation XF-785). Also recommended were seal anti-extrusion rings (uncut) of Tetralon 35313-10 AKA from Tetrafluor, Inc. to be used wherever possible in the FHBS.

The FHBS kit tubing material, 304-1/8 hard CRES, is identical to that used in C/KC-135 aircraft hydraulic system. The kit tubing used the wall thickness schedule adopted for the KC-135R program.

2. RESERVOIR/SEPARATOR DESIGN

The reservoir/separator design evolved through a series of changes prior to the final configuration as discussed in Section III.1. Figure 15 shows a cross-sectional view of the reservoir/separator assembly. The reservoir/separator unique detail parts were manufactured per drawings 180-59836 and 180-59842. Other parts such as O-rings, bolts, washers, backup rings, rod scrapers and piston seals were purchased "off-the-shelf".

The reservoir/separator assembly design contained the following features:

- Positive CTFE/MIL-H-5606 fluid separation.
- Vent of dynamic piston seal leakage.
- Uncut "Tetralon" backup rings.
- Minimize dynamic seal friction and piston inertia.
- CTFE fluid quantity indication.
- Minimize air in CTFE/MIL-H-5606 fluids during maintenance.
- Unaffected by environment of sand, salt fog, high humidity, moisture, ice, -65°F or +160°F ambient, vibration, and "g" loading.
- Metal within the CTFE fluid system does not sweep through a seal(s) into the MIL-H-5606 fluid system, or vice-versa.

The conservatively designed reservoir/separator housing was machined from 15-5PH stainless steel. The internal diameter contained two seal grooves to accommodate the Advanced Products spring-energized plastic seals. These seals, because they are incapable of the deformation normally required for installation in a standard rectangular cross-section gland, required a conical ramp on the high pressure side of the seal such that seal installation can be accomplished. The housing internal diameter also contained a static seal gland of the single backup ring width because of overall length considerations. A half annulus groove was provided for the end cap retention device. The end cap retention design minimizes the length requirement for the end cap and housing. The groove contains a steel annular rod, when assembled, that locks the end cap to the housing.

The reservoir/separator piston and rod subassembly were designed for fluid separation, minimum weight, long wear life and CTFE system air removal. Primary functions of this subassembly were to act as a positive fluid separator between the MIL-H-5606 and the CTFE fluid systems, to provide a dynamic sealing surface(s), to allow air to be bled from the CTFE system, and to provide a means of determining CTFE fluid quantity. The minimum weight requirement was derived from the need to minimize the dynamic mass within the system such that equivalency to the existing brake system dynamics could be achieved. The subassembly was made up of the piston, rod, piston/rod seal, CTFE fluid quantity gage pointer and a bleed valve.

The piston and rod were machined from 7075 aluminum, heat treated to a -T73 condition and anodized. The piston's and rod's external surfaces that contacted dynamic seals were hard (sulfuric acid) anodized to a .002 inch thickness. The remainder of the surfaces were flash hard anodized to a .0003 inch thickness, followed by a sodium dichromate seal process as a protective finish. The piston's exterior bottom was designed concave to allow air in the CTFE fluid system to float upward to the piston rod, and during system servicing, out of the system through a bleed valve mounted at the end of the rod.

The piston/rod static PTFE O-ring seal was selected for compatibility with both hydraulic fluids and has had an excellent service record in this type of application.

The CTFE system bleed valve was a MS28889 valve modified with PNF O-ring seals. The valve metallic parts were made of 303Se CRES.

The reservoir/separator end cap subassembly contains the rod bearing, rod bearing retainer, static seal, rod seal, rod scraper and CTFE fluid quantity gage. This subassembly was designed similar to many actuator rod end caps. The end cap's retention design was derived from a Boeing 757 nose gear retraction actuator. After assembly, a groove in the housing contains an annular steel ring that interfaces with a quarter annulus groove in the end cap which retains the end cap to the housing for the primary load from hydraulic pressure. The end cap is prevented from moving into the housing through the use of three bolts and washers.

The end cap was machined from 7075 aluminum, heat treated to a -T73 condition and flash hard anodized to .0003 inch thickness. The rod bearing and bearing retainer material selected was AMS 4640 aluminum-nickel bronze. This material has shown excellent service experience for this type of application. These parts contain two MS28775 Buna-N O-rings with dual MS27595 TFE backup rings and a C. E. Conover rod scraper ring. The O-ring seals prevent the leakage of MIL-H-5606 fluid. The Conover scraper was selected for its excellent results in excluding airborne dust/grit from the dynamic seal on the rod bearing. The scraper along with the low rod clearance bearing retainer have shown excellent ability to successfully scrape ice from the rod thus preventing damage to the scraper and the dynamic rod seal.

3. RESERVOIR/SEPARATOR INSTALLATION LOCATION SELECTION

The selected reservoir/separator assembly installation location was based upon available space and landing gear/tire clearance considerations. The preferred

location would have been to be very near the existing location of the deboost valve as this installation required a minimum of design effort. However, this installation was not possible due to insufficient space. The closest available space to the deboost valve that was easily accessible to ground service personnel was the aft outboard corner of the wheel well.

In reviewing various schemes for locating the brake shuttle valve, the reservoir/separator and the deboost valve, it was determined from the standpoint of minimizing line length and ease of bleeding air from the two fluid systems; (1) the shuttle valve should remain near its existing location; and (2) the reservoir/separator should be colocated with the deboost valve.

Since system dynamics performance was going to be affected by the lengthening of the brake lines, the tube diameters were increased between the antiskid valve and the brakes. The HSFR computer simulations of the FHBS with the aft located reservoir/separator-deboost valve installation indicated a need for increased tubing sizes in order to maintain frequency response equivalency compared to the existing system. With the larger tube sizes in the FHBS, it was noted that with the significant lowering of fluid line pressure drop came a lowering of the system pressure damping. Reduced damping increases the tendency during brake pressure application to overshoot the desired pressure. This pressure overshoot characteristic has been found to cause secondary tire skids that result in longer aircraft stopping distances. The solution to this secondary skid problem was to introduce into the fluid system a one-way restrictor valve. This valve reduces the pressure rise rate during brake pressure application to prevent the pressure overshoot but, being in the free flow position, does not change the pressure decay rate when brake pressure is removed from a skidding tire.

The relocation of the reservoir/separator-deboost valve installation to the aft outboard corner of the wheel well and the iterative analysis/design process determined the final system design including the plumbing sizes and the one-way restrictor valve.

4. RESERVOIR/SEPARATOR-DEBOOST VALVE INSTALLATION BRACKETS

The installation bracketing for the FHBS reservoir/separator and deboost valve were designed by the C/KC-135 Program design group. The brackets were designed to support the reservoir/separator over the deboost valve for the normal C/KC-135 aircraft installed equipment shock and vibration requirements. The bracketing provided a bottom support for the deboost valve as in the existing support bracket design, and a clamp attachment to the reservoir/separator housing. The brackets were manufactured from standard angle and channel 7075-T6 aluminum extrusions and from brake press formed parts of 7075 aluminum plate heat treated to -T6 after forming. The truss type bracket configuration was the optimum design for cost, weight, strength and rigidity as required for this application.

5. CTFE SYSTEM FILL VALVE

The CTFE fluid system fill valve was required to be sufficiently different from the MIL-H-5606 fluid system fill valves, quick disconnects, etc. so that there would be no chance of inadvertent fluid mixing due to a maintenance or reservoir servicing error. The FHBS was designed with a MS28889 valve modified with PNF O-rings.

6. DEBOOST VALVE MODIFICATION

The deboost valve modifications consisted of changing the O-ring seals to PNF and increasing the exit passage flow area. The deboost valve end cap has four holes through which fluid must flow when the brakes are applied or released. In the HSFR computer simulations, discussed in Section IV.3, excessive flow restriction was noted during release of brake pressure. Since further increases in tube diameters was producing diminishing returns in performance and unacceptable plumbing installation problems, the deboost valve end cap flow passage restriction was reviewed for modification. The hole diameters were reamed to .20 inch diameter from .15 inch diameter for an area increase of 78 percent. This change, when evaluated with the HSFR model, produced a significant improvement in FHBS performance equivalency compared to the existing brake system.

7. CTFE FLUID SYSTEM RESERVOIR SERVICING CART

The FHBS utilizes CTFE nonflammable hydraulic fluid which is not available on the flight line, thus a portable reservoir servicing cart compatible with CTFE was required to perform several maintenance tasks such as CTFE system bleeding of air, reservoir quantity servicing and repaired components pressure testing. A modified TRONAIR manual pump servicing cart (P/N 06-5011-6800) met all the requirements while being cost effective.

The TRONAIR CTFE reservoir servicing cart has the following characteristics:

- Empty Weight - 75 pounds.
- Two Stage Pump - 2.2 cubic inches per stroke up to 500 psi and 0.38 cubic inches per stroke up to 4000 psi.
- Filtration - 3 micron absolute
- Reservoir Capacity - 13 gallons
- Service Hose Length - 15 feet.
- Pressure Gauge - to 5000 psi.
- Viton O-ring seals.
- 10 inch diameter wheels
- 303 Stainless Steel Tank.

V. PRELIMINARY FHBS DOCUMENT AND REPORTS

As discussed earlier in this report, there was a preliminary phase to the FHBS program that was documented as follows:

1. PRELIMINARY HAZARD ANALYSIS

The Preliminary Hazard Analysis (PHA), Reference 3, was prepared in accordance with MIL-STD-882A and documented the initial safety assessment of potential failures. The purpose of the analysis was to identify and evaluate the potential hazardous areas for more detailed attention in subsequent hazard analyses and design activities.

2. CLASS II MODIFICATION PRELIMINARY DESIGN DATA (PART I)

The preliminary modification document, Reference 4, was prepared in accordance with DI-E-3115B/M as modified by Reference 1 (FHBS proposal) and the contract F33615-83-C-2322 Statement of Work. The document contained the preliminary design and analysis of the FHBS. Presented was a narrative description of the proposed modification, preliminary installation and component design drawings, schematic drawings for interfaces, instrumentation and system description, a weight/balance summary for the two candidate test aircraft, stress analysis of the reservoir/separator assembly and the reservoir/separator-deboost valve installation bracketry, and a plan for demodification of the FHBS.

3. INTERIM TECHNICAL REPORT

The interim report, Reference 5, documented all aspects of the FHBS research/development program from its inception in July 1983 thru the preliminary design/analysis phase in February 1984. The report presented the details of all activities relating to the FHBS CTFE fluid replenishment system concepts trade study which ultimately resulted in the FHBS design.

The trade study evaluated the proposal replenishment system concept plus two alternate reservoir concepts as well as five alternate valve/system concepts. The evaluation analyzed the candidates for weight, cost, reliability maintainability, serviceability, safety, ease of installation, developmental risk, dynamic performance, mixed fluid potential and demodification time and cost.

4. ORAL REPORT

An oral report of the preliminary program phase was presented at Wright Patterson AFB on January 11, 1984 and covered all contract activities. Discussed were the aspects that led to the change from the proposal FHBS replenishment concept to the recommended reservoir/separator concept. The highlights of the Class II Modification preliminary design data and analysis document were presented. Boeing recommendations regarding flight tests included that the FHBS test kit be installed on the left outboard wheel pair (forward and aft wheels), and a list of the minimum instrumentation required for flight test.

5. CONCLUSIONS AND RECOMMENDATIONS

At the completion of the preliminary program phase, Boeing recommended continuation of the program with the Alternate 5 - reservoir/separator FHBS concept with a restrictor check valve. The recommendation was based upon the conclusions of the Task 1 - FHBS Design trade study. This task incorporated the recommendations of Task 2 - Frequency Response Analysis, Task 3 - Modification Documentation, Task 4 - Preliminary Hazard Analysis, and Task 11 - Reliability/Maintainability Study.

VI. LABORATORY TEST PLANS

The FHBS contract required laboratory test plans for component and system flightworthiness be presented to and approved by the Air Force.

1. COMPONENT FLIGHTWORTHINESS TEST PLAN

A test plan (Appendix B) for all new and modified FHBS components was required to assure their flightworthiness for a C/KC-135 flight test installation. The test plan contained the applicable test requirements of MIL-H-8775. All components containing CTFE nonflammable hydraulic fluid required seals molded from modified PNF material. Those components with PNF seals but not otherwise modified, such as the brake assemblies, relief valve, deboost valve and the MS28889 fill and bleed valves, were proof pressure and leak tested and, where applicable, functionally checked.

The new designed components were to be evaluated by structural, performance and life cycle testing. Structural testing constituted proof pressure, normal and maximum brake pressure cycling and vibration testing per D-16046, "Vibration Test Requirements for Items of Equipment Installed in Model KC-135 Airplanes". Performance tests at room, maximum and minimum temperatures were required to determine the FHBS equivalency to the "as built" C/KC-135 brake system. Component life cycle tests were to be conducted as a system test where all components were subjected to the test simultaneously.

2. SYSTEM FLIGHTWORTHINESS TEST PLAN

a. Baseline Tests--The FHBS contract required that the braking performance of the two-fluid brake system be equivalent to the existing C/KC-135/MIL-H-5606 fluid brake system. The baseline tests provided the braking performance data for the "as-built" C/KC-135 system. These data were required to provide the baseline for evaluating the performance equivalency of the FHBS.

System step and frequency response, constant friction and step friction stopping performance, and landing gear stability characteristic tests were to be conducted at room temperature, 160^{O}F, and -65^{O}F. Since seal leakage was experienced during testing at -65^{O}F on a similar system, the test plan includes a contingency procedure for determining the minimum temperature to successfully conduct the test.

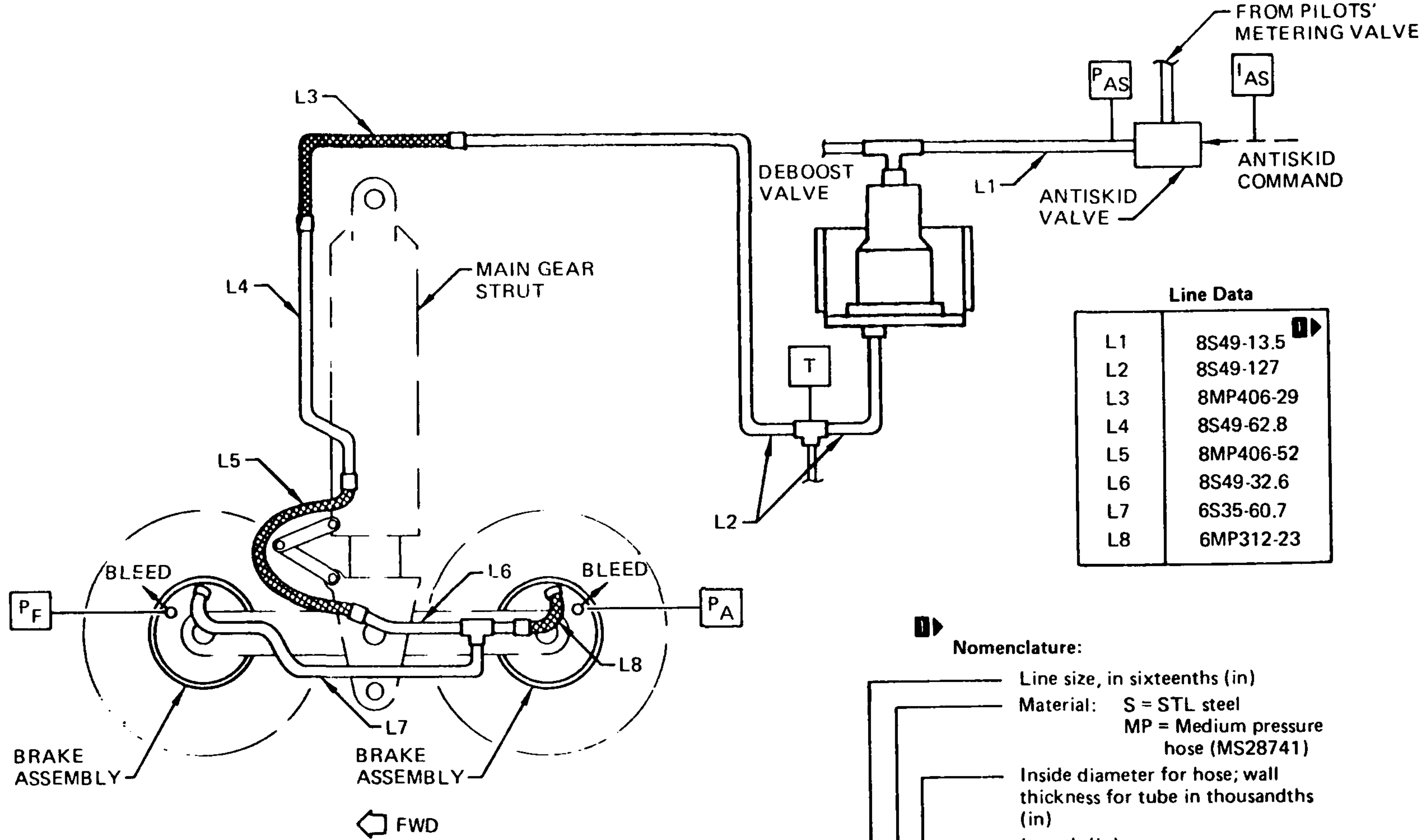
The general arrangement of the brake hydraulic system test setup is shown in Figure 17. The line lengths and diameters are the same as measured on the aircraft selected for flight test; C-135 tail number 60-0375.

Details of the planned test program, test conditions, and the test setup are provided in Appendix C.

b. Fill, Bleed, and Servicing Procedure--As part of the system test plan, a fill, bleed and servicing procedure was to be developed to refine and finalize the procedure for the test aircraft. The Technical Order (TO) detailing the servicing and checkout of the "as-built" brake system was utilized as a guide where possible. Procedures for the CTFE fluid system were specified such that flight line maintenance personnel could accomplish the tasks. A CTFE service cart was provided with the FHBS kit to accomplish the pressure testing of components, bleeding air from the CTFE system and servicing the CTFE reservoir.

c. One-Way Restrictor Valve Orifice Sizing Test--This testing was conducted on a laboratory simulation of the FHBS design to determine the diameter of the orifice in the one-way restrictor.

As described in Section IV, a one-way restrictor was included in the FHBS design to improve stopping performance. A design analysis predicted an orifice diameter of 0.16 inch. However, this analysis technique (using steady flow coefficients in an oscillatory flow case) has never proved to be very accurate thus a test was performed to determine the correct orifice diameter.



Line Data

L1	8S49-13.5 ■▶
L2	8S49-127
L3	8MP406-29
L4	8S49-62.8
L5	8MP406-52
L6	8S49-32.6
L7	6S35-60.7
L8	6MP312-23

■▶ **Nomenclature:**

X Y Z – L

- X — Line size, in sixteenths (in)
- Y — Material: S = STL steel; MP = Medium pressure hose (MS28741)
- Z — Inside diameter for hose; wall thickness for tube in thousandths (in)
- L — Length (in)

[P] Pressure transducer
[T] Temperature transducer
[I] Current

Figure 17. As-Built KC-135 Brake Hydraulic System Mockup Data

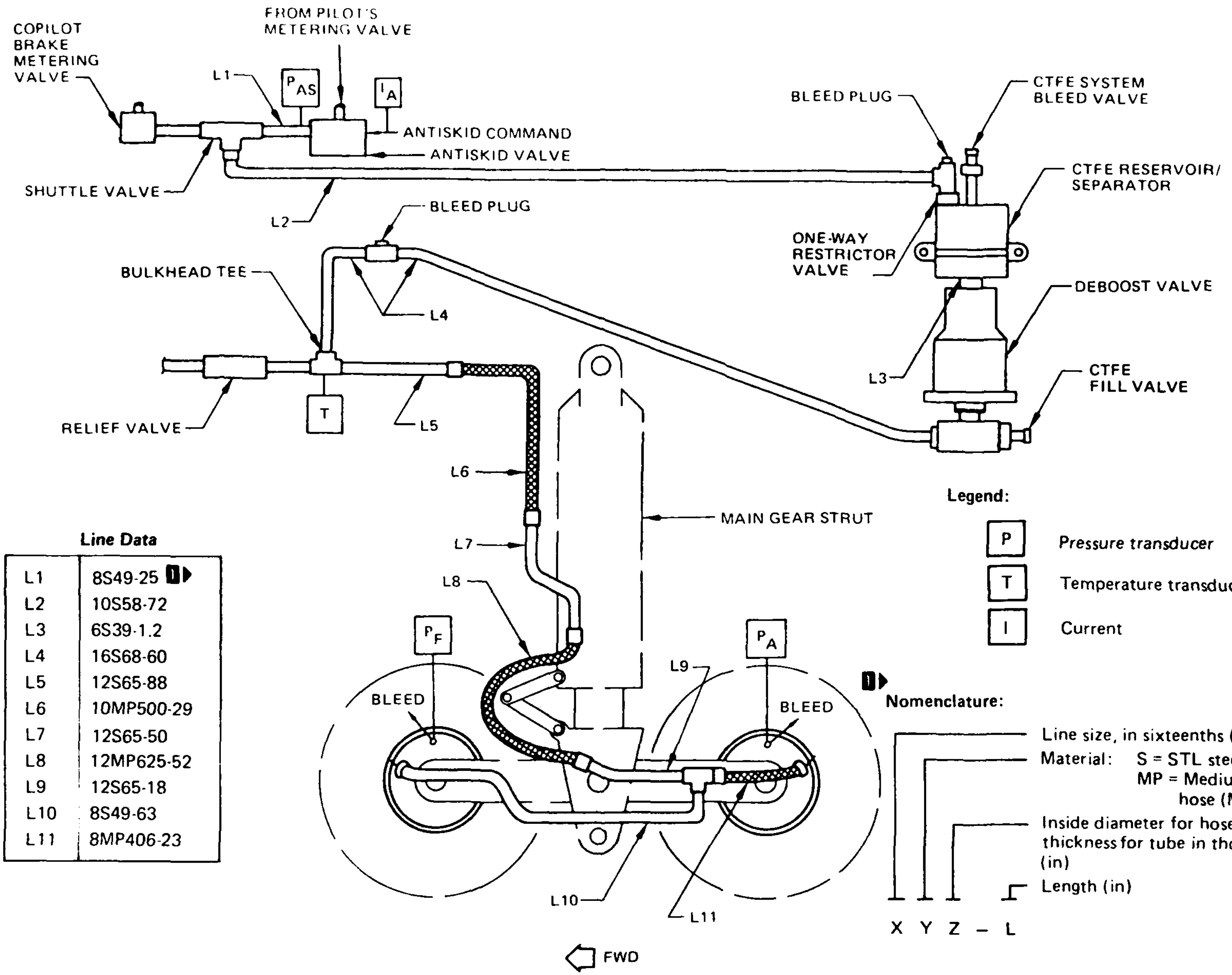
The test plan required constant friction stopping performance and system response to a step command tests. The initial tests were to be conducted with the poppet and retainer removed from the one-way restrictor valve. For subsequent tests the poppet and retainer were to be installed and testing initiated with an orifice diameter of 0.10 inch. These tests were to be conducted at room temperature. Details of the test program and the test setup are provided in Appendix C. The general arrangement of the FHBS system laboratory setup is shown in Figure 18.

d. Performance Tests--Following selection of the one-way restrictor orifice diameter, a series of performance tests of the FHBS were to be conducted at room temperature, 160°F and -65°F. Since seal leakage was experienced during testing at -65°F on a similar system, the test plan includes a contigency procedure for determining the minimum temperature to successfully conduct the test. These tests included system step and frequency response, constant friction and step friction stopping performance, and landing gear stability characteristics.

Also conducted was an intermediate temperature/icing test. This test was to be initiated following the minimum temperature performance tests. The test system was to be rapidly warmed to 160°F. During the system warmup, frequency response tests were to be conducted at -30°F, 0°F, 30°F, 60°F, 100°F, and 125°F. When the temperature was less than 25°F, the FHBS was to be sprayed with water and the motion of the reservoir/separator rod observed for evidence of sticking and fluid leakage around the rod seal.

Details of the test program, test conditions and test setup are provided in Appendix C.

e. Endurance Tests--The endurance tests were required to determine the system's ability to operate without failure or degradation for the many operational cycles expected in the life of the aircraft. As specified in the test plan (Appendix C), the system was to successfully complete 100,000 normal brake pressure applications and 5000 maximum brake pressure applications. CTFE fluid sampling was required prior to initiating tests, at the middle and end of normal pressure endurance cycling, and at the end of the maximum pressure cycles.



Line Data

L1	8S49-25 1▶
L2	10S58-72
L3	6S39-1.2
L4	16S68-60
L5	12S65-88
L6	10MP500-29
L7	12S65-50
L8	12MP625-52
L9	12S65-18
L10	8S49-63
L11	8MP406-23

Legend:

- P — *Pressure transducer*
- T — Temperature transducer
- I — Current

1▶ **Nomenclature:**

X Y Z – L

- X — Line size, in sixteenths (in)
- Y — Material: S = STL steel; MP = Medium pressure hose (MS28741)
- Z — Inside diameter for hose; wall thickness for tube in thousandths (in)
- L — Length (in)

Figure 18. Two-Fluid Brake Hydraulic System Mockup Data

f. Post Test Inspection--An inspection of all wearing surfaces was required by the plan to determine the life expectancy of those parts. Photographs of all disassembled components was to be added to the test record.

VII. COMPONENT FABRICATION

The FHBS was designed for a minimum number of new or unique components. Second, these unique components utilized uncomplicated design, and materials, processes and finishes whose properties are well known. The only major new component in the FHBS was the reservoir/separator. Other FHBS unique components included the reservoir/separator-deboost valve installation brackets, the deboost/fill valve tee, an adapter and the one-way restrictor. All other components were standards parts (military, SAE or C/KC-135).

1. RESERVOIR/SEPARATOR FABRICATION

The reservoir/separator components were fabricated by Aircraft Standards, Seattle, WA following a three company bid and selection process. The reservoir/separator components were detail designed, drawing 180-59836, as discussed in Section IV.2. A photograph of the reservoir/separator components is shown in Figure 19. Two each of all parts were purchased for the FHBS program, except for three rod bearings (180-59836-5) and three bearing retainers (180-59836-6). These quantities were felt to be adequate for the program. Additional quantities of the rod bearings and bearing retainers were purchased as these parts had a higher probability of damage during assembly and/or wear during the endurance test or in service.

A modification to the housing to add ramps for piston seal installation was done as a rework item within Boeing manufacturing shops.

2. RESERVOIR/SEPARATOR - DEBOOST VALVE INSTALLATION BRACKETS FABRICATION

Brackets for the reservoir/separator-deboost valve installation were fabricated within the Boeing manufacturing shops as this was judged to be the most cost effective. The brackets design details are on drawings 180-59851 and 180-59852. These parts were manufactured from AND standard aluminum extrusions or simple, flat pattern, brake formed parts as indicated on the drawings.

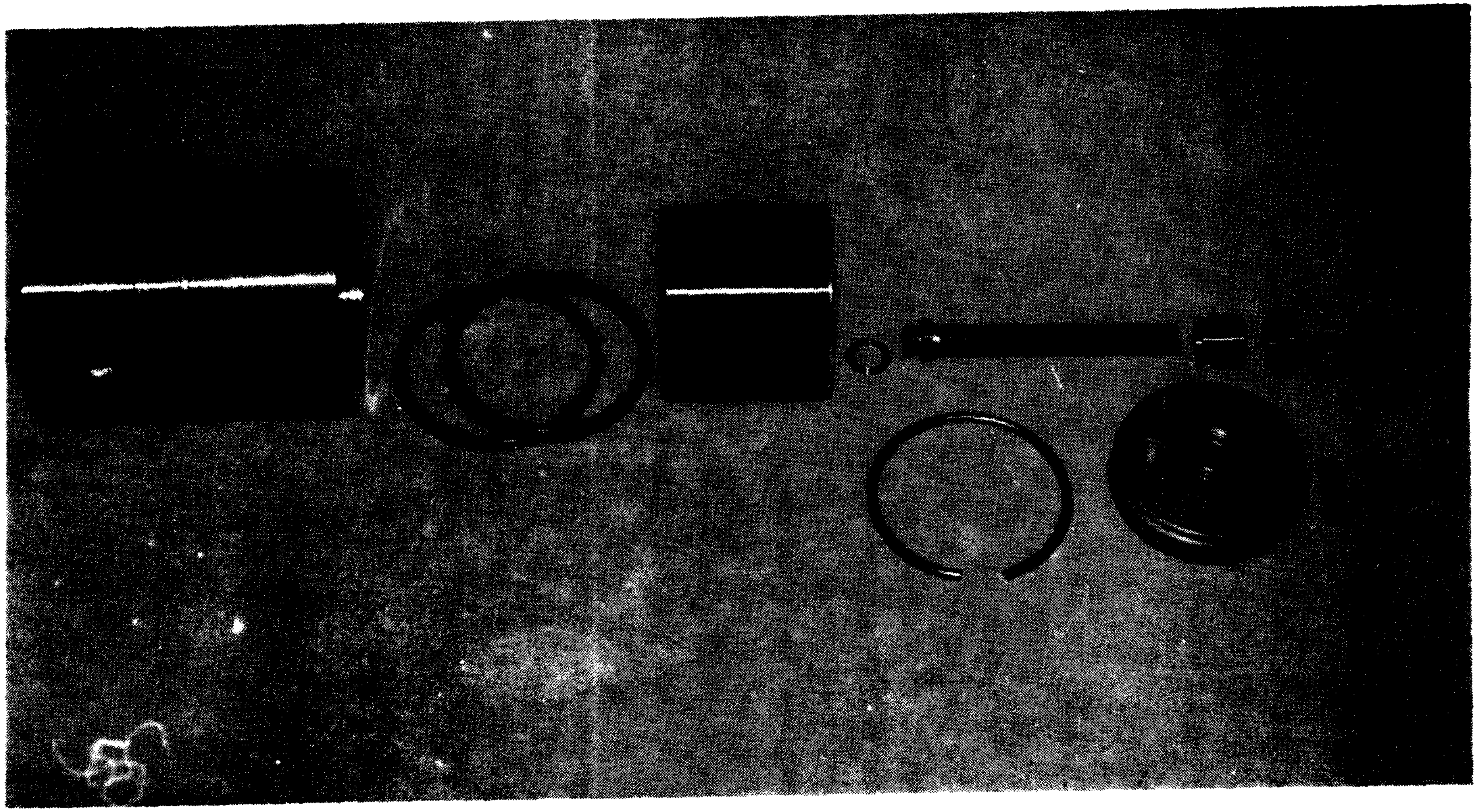


Figure 19. Parts For Reservoir/Separator Assembly

3. DEBOOST VALVE/FILL VALVE TEE FABRICATION

A special fitting was fabricated per drawing 180-59841 by Aircraft Standards, Seattle, WA. The fitting was a unique design to accommodate the 3/8 inch deboost valve port, a one inch hydraulic tube and the modified MS28889 CTFE fill valve.

4. ONE-WAY RESTRICTOR VALVE FABRICATION

A "make-from" check valve was delivered from Crissair, El Segundo, CA. unassembled for modification at Boeing. The check valve assembly consisted of three components; the housing, the valve poppet and a poppet retainer. The poppet was modified by electro-discharge machining (EDM) an orifice to provide an optimum increase in brake pressure during antiskid cycling. Boeing drawing 180-59839 specified the poppet rework and the one-way restrictor valve assembly.

5. COMPONENT REWORK FOR SEAL CHANGE

Several components of existing C/KC-135 design required rework to replace seals not compatible with CTFE fluid with PNF seals. The following components were disassembled, O-ring seals removed, cleaned, PNF O-rings installed, reassembled and functionally tested per the indicated Boeing drawing.

Component Nomenclature	Boeing Drawing Number
Brake Assembly	180-59845
Deboost Valve	180-59838
Relief Valve	180-59844
Fill/Bleed Valve	180-59843

VIII. COMPONENT FLIGHTWORTHINESS TEST RESULTS

The following section relates the results of the component flightworthiness qualification tests conducted following the FHBS Component Flightworthiness Test Plan contained in Appendix B and discussed in Section VI.1.

1. EXAMINATION OF PRODUCT

All components were inspected by Boeing Receiving Inspection and found to meet drawing requirements.

2. PROOF PRESSURE AND LEAKAGE TEST RESULTS

The FHBS components passed the proof pressure and/or leakage tests specified in the Appendix B - FHBS Component Flightworthiness Test Plan or the assembly drawing as noted in Table 3.

3. VIBRATION TESTS

Although no vibration testing was anticipated for the FHBS program in the Boeing proposal (Reference 1), the Air Force required vibration testing of the entire reservoir/separator-deboost valve installation including support brackets. Therefore, vibration testing was included in the Air Force-approved FHBS Component Test Plan.

The FHBS reservoir/separator-deboost valve installation, including all mounting bracketry, was subjected to a vibration test per the requirements of D-16046, "Vibration Test Requirements for Items of Equipment Installed in Model KC-135 Airplanes", <u>Group 9</u> (equipment installed in the wheelwell), <u>Category A</u> (equipment rigidly mounted to airplane structure). The test procedure required the equipment be vibrated in each of three mutually perpendicular directions to explore for resonant frequencies of the component parts. The scans were slowly swept between 5 and 1000 Hz such that each resonant frequency of the instrumented parts were determined for endurance testing. Photographs of this vibration test setup are shown in Figures 20, 21, and 22.

Table 3. Component Leakage and Proof Pressure Test Results

Part number	Nomenclature	Test pressure (psi)	Leakage
180-59837-1	Reservoir/separator	4500 [1] [2]	0
180-59837-1	Reservoir/separator	4500 [1] [3]	0
180-59837-1	Reservoir/separator	3000 [4]	0 at CTFE port < 1 drop from weep holes
180-59837-1	Reservoir/separator	5 [4]	0 at CTFE port 1 drop from weep holes
180-59838-1	Deboost valve	4500 [1] [5]	0
180-59838-1	Deboost valve	1445 [1] [6]	0
180-59838-1	Deboost valve	5	0
180-59838-1	Deboost valve	±5 (25 cycles) [7]	0
180-59839-1	Restrictor/check valve	4500 [1]	0
180-59840-1	Restrictor/check valve adapter	6000 [1]	0
180-59841-1	Deboost/fill valve tee	6000 [1]	0
180-59843-1	Fill and bleed valve	4500 [1]	0
180-59844-1	Relief valve	3750 [1]	0
180-59844-1	Relief valve	2	0
180-59845-1	Brake assembly	1800 [1]	0
180-59845-1	Brake assembly	2	0
180-59845-1	Brake assembly	0-1200 (25 cycles) [7]	0

Notes:

[1] Proof pressure
[2] Pressure on MIL-H-5606 fluid side of piston only
[3] Pressure on CTFE fluid side of piston only
[4] Four hour intrasystem leakage test
[5] Small diameter end only
[6] Large diameter end only
[7] Dynamic seal leakage test
[8] All assemblies of same P/N had same leakage results

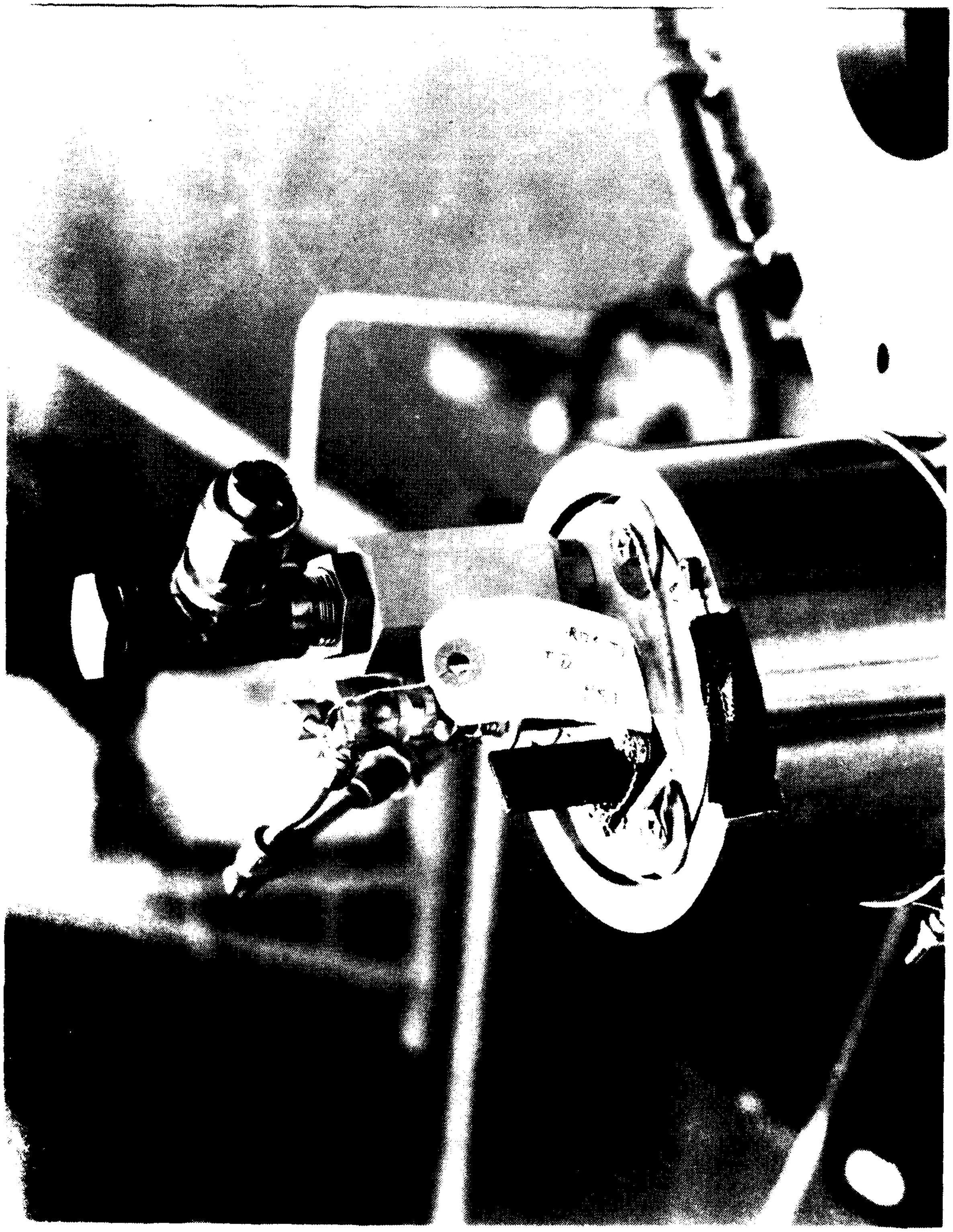


Figure 20. Reservoir/Separator Vibration Test Setup – Top Details

Figure 21. Reservoir/Separator Vibration Test Setup – Shaker Mounting

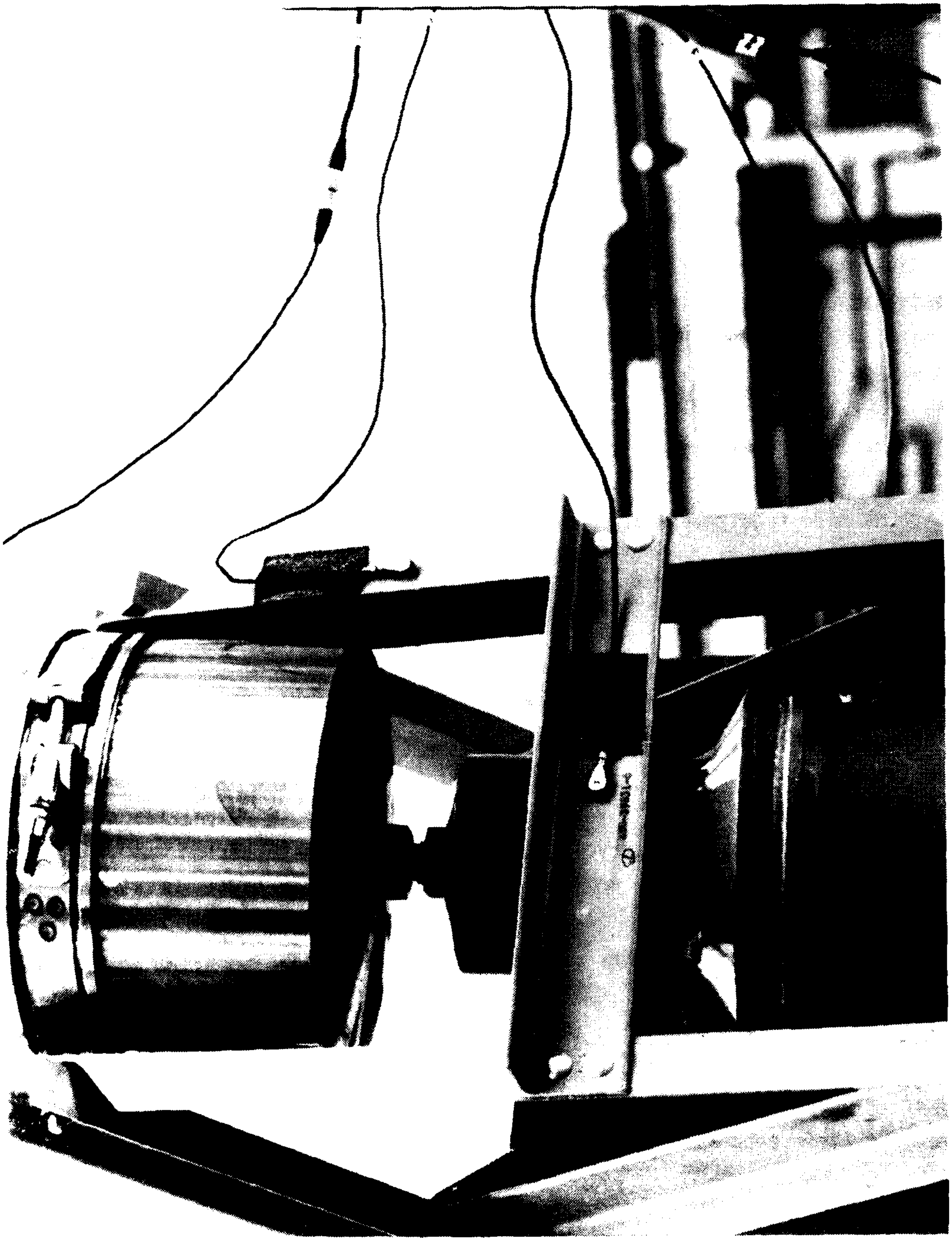


Figure 22. Reservoir/Sepatator Vibration Test Setup – Inboard Face

The resonance endurance test requirements specify that one million vibration cycles were to be subjected to the equipment at each of the resonances. The one million vibration cycles constituted infinite airframe life at the resonant frequency(s). Since the C/KC-135 airframe was designed for 20,000 flight hours and the test installation of the FHBS kit will not exceed 1000 flight hours, Boeing recommended 1/20 of the one million cycles (1000/20,000), or 50,000 vibration cycles, be run at each resonance.

Initial attempts to determine the resonant frequencies of the test installation resulted in several failures of the band clamp stud retaining clips for supporting the reservoir/separator. A new design support clamp (180-59998-1) for the reservoir/separator and several design improvements in the bracket assembly were implemented to stiffen and strengthen the support bracketry. Also, since the hydraulic plumbing added significant stiffness, the test installation incorporated that assembly. Relief from the full airframe life requirement was requested by Boeing (as discussed above) and received.

An additional unsuccessful attempt was made which resulted in a bracket failure. Examination of the fractures in the P/N 180-59852-2 and -3 indicated that the cracks had been initiated some significant time before the vibration tests. This dove-tailed with the approximate time when the performance testing was initiated using the same set of hardware. The system plumbing and components were not adequately supported thus resulting in significant shaking of the test setup. The reservoir/separator-deboost installation was particularly prone to large motion amplitudes in the direction that would cause the bracket(s) fatigue crack(s) to initiate. Also, these brackets were the same parts used during the band clamp clip failures discussed earlier.

The final successful vibration test was initiated with the unused set of brackets. (A new set of brackets was manufactured for the aircraft.) The detail vibration testing report is contained in the Part II Modification Document (Reference 8).

4. ENDURANCE CYCLING

Endurance cycling of the FHBS's unique components was deferred to the system flightworthiness testing such that all components could be tested in concert for a minimal cost impact on the program. As all system components were already qualified using MIL-H-5606 fluid, or were of mature, state-of-the-art design, no endurance cycling problems were expected using this approach.

IX. SYSTEM FLIGHTWORTHINESS TEST RESULTS

1. GENERAL DISCUSSION

System flightworthiness tests were performed per the Air Force-approved test plan (Appendix C) as discussed in Section VI.2. The testing was conducted in two phases; C/KC-135 baseline tests, and FHBS tests. The baseline test results were required to quantify the performance of the C/KC-135 Mark II, five rotor brake system. These performance results were then used as the basis to which the FHBS had to show equivalency.

a. Component Tests--Some component flightworthiness testing was integrated into the system flightworthiness tests as discussed in the FHBS Component Flightworthiness Test Plan (Appendix B) and Sections VI.1 and VIII.4. The reservoir/separator (P/N 180-59837-1) had the following component flightworthiness test requirements completed as a system flightworthiness test: intermediate, maximum and minimum temperature performance, and icing tests. Since the reservoir/separator parts making up the test speciman were to be delivered as spares for the flight test kit, the planned endurance cycle test (Appendix B) was deleted to prevent excessive reduction in the life of these components.

b. Description of Test Rig--The brake system flightworthiness performance tests were conducted using a brake hydraulic system mockup. A mockup was built for each system tested using standard C/KC-135 components, listed in Table 4, and tube and hose assemblies that duplicated the diameters, wall thickness, length, tube bend geometry, and materials of the actual system hardware. The mockups were mounted on a table for inserting in an environmental chamber.

The mockup for the specific system being tested was integrated with a C/KC-135 Mark II antiskid control unit and a hybrid computer simulation of airplane body, aerodynamic, flight control and landing gear dynamic characteristics to form the C/KC-135 airplane simulation used for these performance tests.

TABLE 4 C/KC-135 BRAKE HYDRAULIC SYSTEM MOCKUP COMPONENTS

ITEM	NATIONAL STOCK NUMBER	QUANTITY
Skid Control Box (Not shown in Figures 17 or 18)	1630-00-918-0340	1
Pilot Metering Valve	1630-00-610-7199	1
Dual Antiskid Valve	1630-00-908-9999	1
Deboost Valve	1650-00-570-8397	1
Accumulator	1650-00-584-9343	1
Brake Assembly	1630-00-058-5242	2

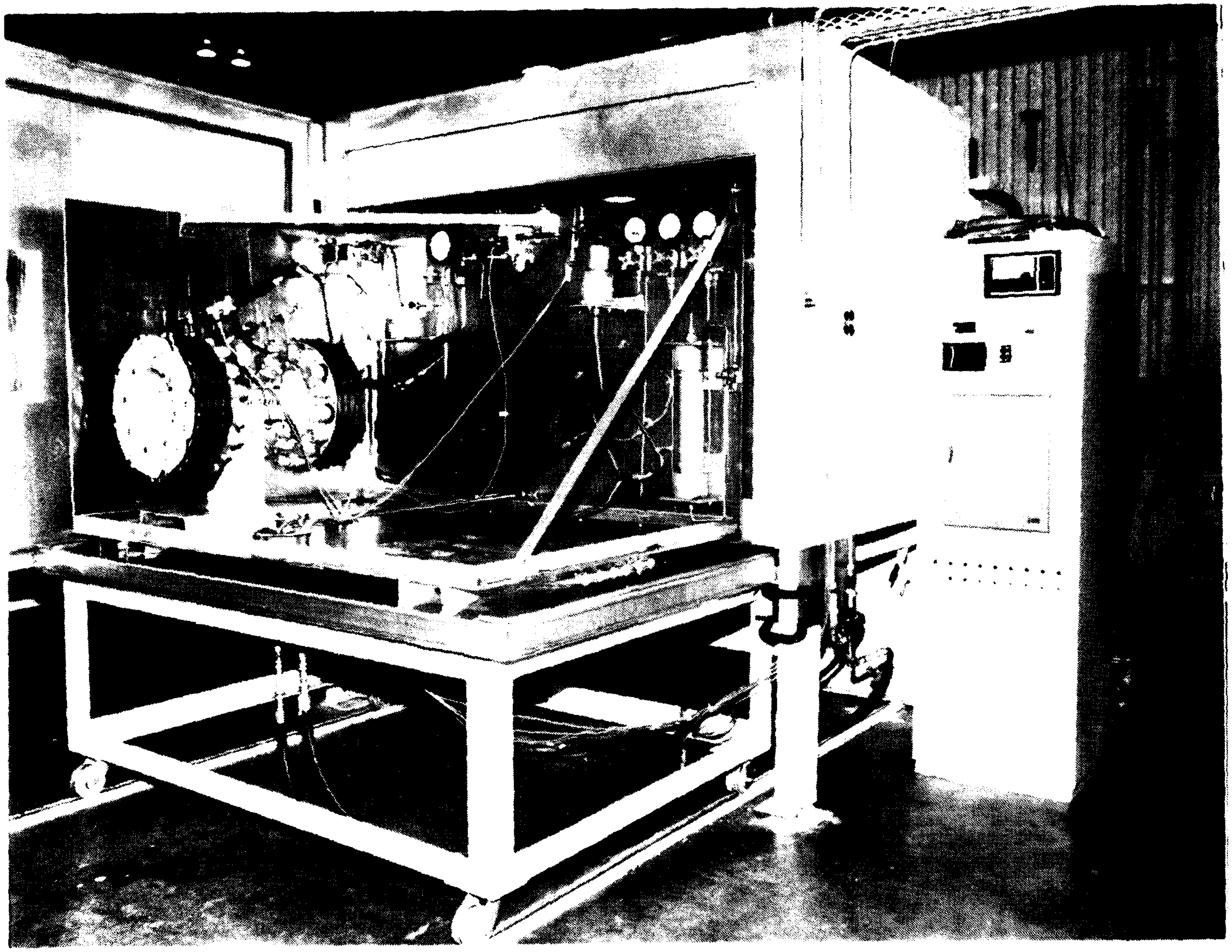


Figure 23. As-Built KC-135 Brake System Test Setup

2. BASELINE TESTS

a. Test Rig Description--The baseline test system duplicated the as-built configuration of the brake hydraulic system to the left outboard wheelpair for C-135 tail number 60-0375. The general arrangement of the test mockup is shown in Figure 17 and a photograph of the test setup is shown in Figure 23.

b. Performance Tests--Brake system tests were performed at room temperature, 160°F, and -40°F. The ambient temperature tests were performed with a room temperature of 68 to 71°F. For high temperature testing, the Thermatron environmental chamber had been at 162°F for more than 14 hours prior to the start of testing. The chamber temperature varied from 162 to 157°F over the seven hour test period.

The test plan called for the low temperature testing to be performed at -65°F. However, when that was attempted, hydraulic fluid leaked from several brake pistons of the aft wheel brake and from the antiskid servovalve housing face seal. Following the low temperature seal leakage contingency procedure in the approved test plan, Appendix C, testing was attempted at -55°F, -45°F, and -40°F. The leakage continued as before at -55°F. At -45°F there was significantly less leakage at the brake pistons. At -40°F, the brake housing leakage was not noticeable and the antiskid servovalve face seal leakage was significantly reduced under static pressure. After commanding the servovalve at 0.5 Hz for approximately one minute, no leakage was visable at the face seal. All subsequent low temperature testing was done at -40°F.

The Thermatron chamber was at -41°F for 8 hours and 20 minutes prior to testing. The chamber remained at -41°F overnight before completing the performance tests. At the beginning of each test period the fluid temperature was -41°F and during the test period increased to -38°F.

The dynamic response test conditions are summarized in Table 5 and the stopping performance test conditions are summarized in Table 6.

Table 5. Brake System Dynamic Response Testing

Test description	Test temp, °F			Test condition (brake pressure)	Output data ①	Number of tests each temp
	-40	Amb	160			
1.0 Frequency response				0.5 to 50.0 Hz		
1.1 As-built system	X	X	X	325 $\pm$ 100 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
	X	X	X	650 $\pm$ 200 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
1.2 Two-fluid system without check valve poppet		X		325 $\pm$ 100 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
		X		650 $\pm$ 200 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
1.3 Two-fluid system	X	X	X	325 $\pm$ 100 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
	X	X	X	650 $\pm$ 200 psi	Transfer functions P_B/P_A, P_B/I_A, P_A/I_A	3
2.0 Transient (step) response				% Max brake pressure		
2.1 As-built system	X	X	X	0-50-0 0-80-0 0-100-0 20-50-20 20-80-20 20-100-20 50-80-50 50-100-50	P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A P_A, P_B, I_A	3 3 3 3 3 3 3 3
2.2 Two-fluid system without check valve poppet		X		20-80-20 20-100-20	P_A, P_B, I_A	3
2.3 Two-fluid system	X	X	X	Same commands as 2.1	P_A, P_B, I_A	3

① **Nomenclature**

I_A–Antiskid valve current
P_A–Antiskid valve pressure out
P_B–Brake pressure

Table 6. Brake System Performance Testing

Test description	Test temp, °F			Braking condition	Output data ①	Number of tests each temp
	-40	Amb	160			
1.0 Constant Mu stopping						
1.1 As-built system	X	X	X	Mu = 0.6, 0.5, 0.4, 0.3, 0.2, and 0.1	P_A, P_B, IA, ω_W, and stopping dist	3
1.2 Two-fluid system without check valve poppet		X		Mu = 0.6, 0.5, 0.4, 0.3, 0.2, and 0.1	P_A, P_B, IA, ω_W, and stopping dist	3
1.3 Two-fluid system	X	X	X	Mu = 0.6, 0.5, 0.4, 0.3, 0.2, and 0.1	P_A, P_B, I_A, ω_W, and stopping dist	3
2.0 Step Mu stopping						
2.1 As-built system	X	X	X	Mu step .5 to .1 per Fig 21. (a)	P_A, P_B, I_A, ω_W, and stopping dist	3
2.2 Two-fluid system	X	X	X	Fig 21. (a)	P_A, P_B, I_A, ω_W, and stopping dist	3
	X	X	X	Fig 21. (b)	P_A, P_B, I_A, ω_W, and stopping dist	2
3.0 Strut stability						
3.1 As-built system	X	X	X	Damping ratio .707 to 0.0; Brake torque pulses: Mu = 0.5	P_B, I_A, T_B, ω_W, and strut disp	3
3.2 Two-fluid system	X	X	X	Damping ratio .707 to 00.0; Brake torque pulses: Mu = 0.5	P_B, I_A, T_B, ω_W, and strut disp	3

① **Nomenclature**
I_A–Antiskid valve current
P_A–Antiskid valve pressure out
P_B–Brake pressure
T_B–Brake torque
ω_V -Wheel speed

(1) Frequency Response-- Tests were performed on the "as-built" brake hydraulic system to determine the dynamic response of the baseline systems to a sinusoidal command signal to the antiskid control valve.

A D. C. electrical control signal corresponding to the desired steady-state pressure level was applied to the antiskid valve. A 0.5 Hertz sinusoidal electronic signal was superimposed on the D. C. signal. The amplitude of the sinusoidal signal was adjusted until the desired sinusoidal pressure amplitude of the brake was obtained. The frequency of the sinusoidal signal was varied between 0.5 Hertz and 50 Hertz. The frequency response in terms of gain and phase shift was determined for the antiskid valve, the brake hydraulic system, and the total brake system, as shown in Table 5.

During initial frequency response testing of the "as-built" system, the antiskid valve frequency response was substantially different than that obtained during the previous test program (Reference 2). Checking of the test setup determined that the brake hydraulic system was connected to port B-1 of the antiskid valve rather than the specified port B-2, which was used during the previous testing. A comparison of the response of the antiskid valve at port B-1 to that at port B-2 is shown in Figures 24 and 25. In Appendix D, Figure D.1 shows typical antiskid valve response (Port B-2) at the three test temperatures. Figures D.2 thru D.7 give test results for the brake system. Likewise, Figure D.8 thru D.13 give test results for the brake hydraulic system.

(2) Step Response--Tests were performed to determine the dynamic response of the brake hydraulic system to a step change in the antiskid valve control signal.

A D. C. electrical control signal corresponding to the initial brake pressure test level was applied to the antiskid valve. The control signal was then stepped up or down to a level corresponding to the final pressure level. The step response test conditions and test points are given in Table 5.

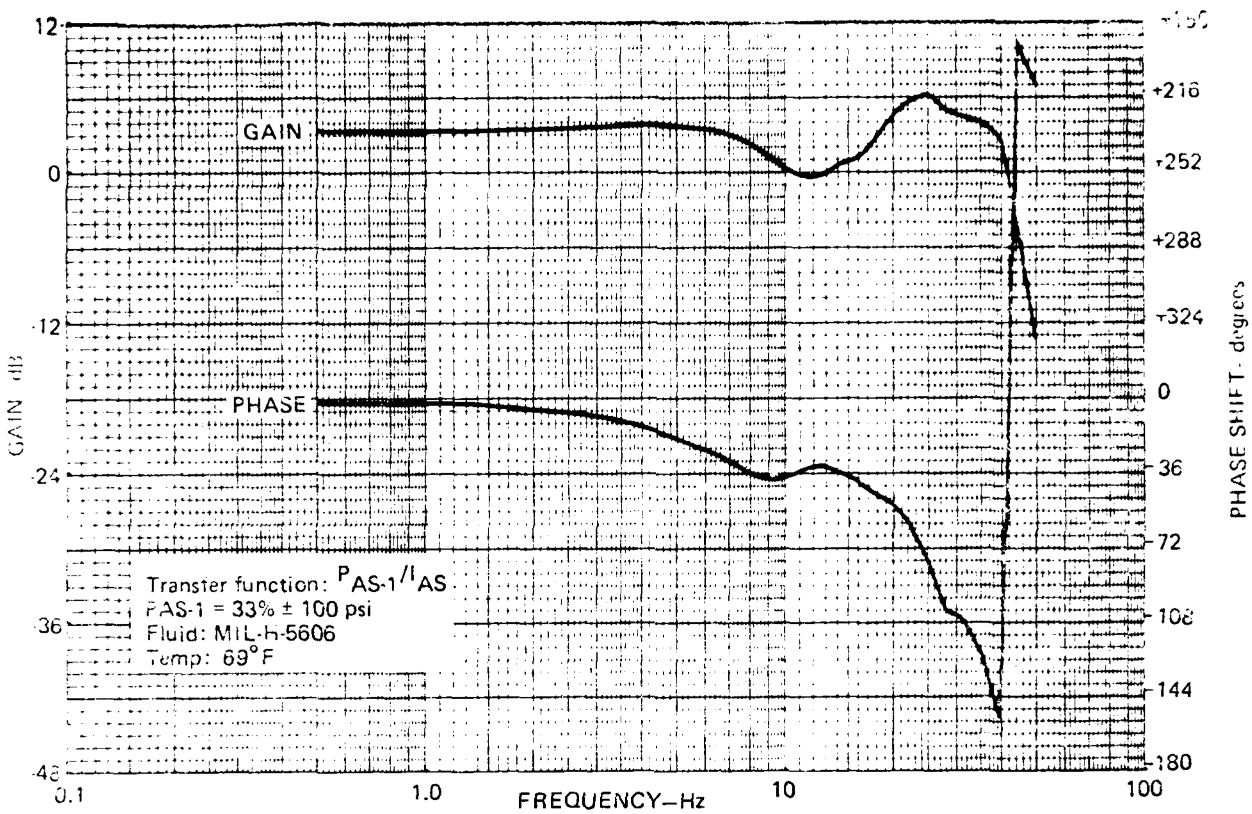


Figure 24. Antiskid Valve Frequency Response at Port B-1

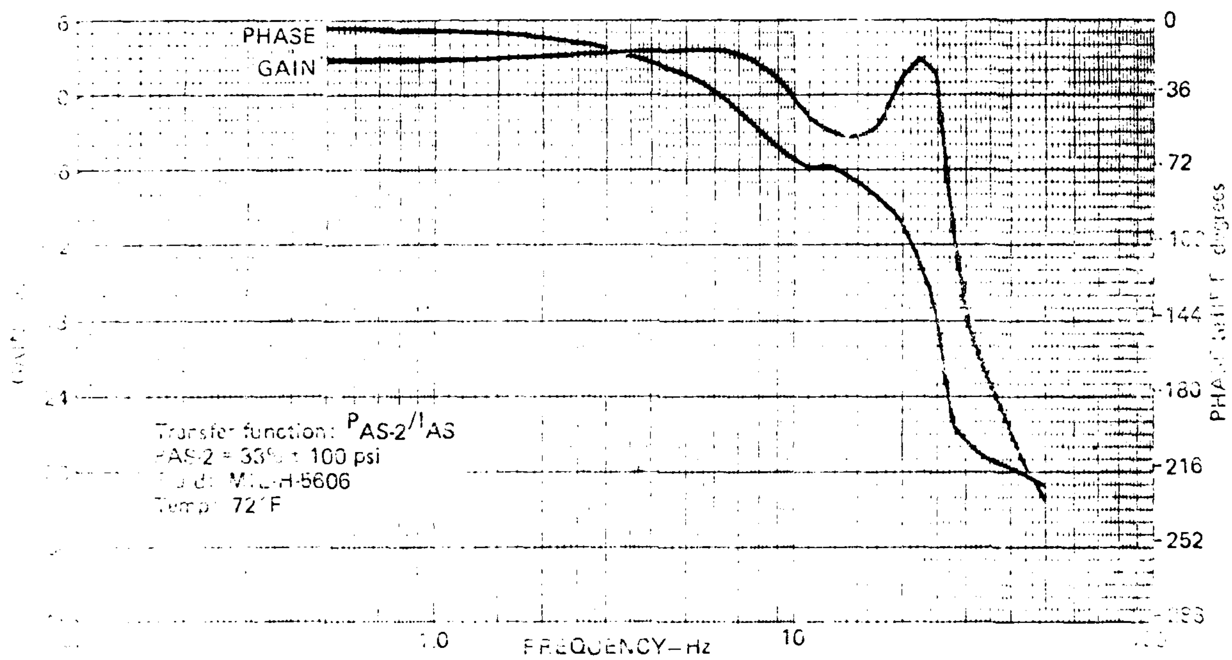


Figure 25. Antiskid Valve Frequency Response at Port B-2

The response of the brake system (at several test points) to a step pressure change command occurring at time zero is shown in Figures D.32 thru D.79 in Appendix D. These figures also show, for direct comparison, the step response data from the two-fluid system testing.

(3) Constant Friction Stopping Performance--The stopping performance of the C/KC-135 aircraft was determined as a function of the runway-tire friction coefficient.

During these tests, braking was initiated two seconds after touchdown and continued until the aircraft decelerated to a typical turnoff velocity (24 feet per second). The peak available friction coefficient was held constant throughout the entire run. The distance traveled from brake application to 24 feet per second was recorded.

The test was performed at room temperature, -40°F and +160°F. The test results are given in Table 7. Typical time history plots of wheel speed, brake pressure and antiskid valve current at each runway friction coefficient and ambient temperature are given in Appendix D, Figures D.14 thru D.19. Similar results at low temperature (-40°F) and high temperature (+160°F) are given in Figures D.20 thru D.25 and Figures D.26 thru D.31 respectively.

(4) Stepped Friction Performance--The stopping performance and adaptability of the C/KC-135 brake system to a step change in runway friction (simulating icy patches or tar strips) was determined. For these tests the peak available runway friction coefficient for an otherwise normal braked landing was varied in the step fashion shown in Figure 26(a). The distance from brake application to 24 feet per second was recorded.

The test was performed at room temperature, -40°F and +160°F. The stopping distance test results are given in Table 8. Typical time history plots of wheelspeed, brake pressure, antiskid valve current and the peak runway friction coefficient at ambient, -40°F and +160°F are given in Figures 27, 28, and 29 respectively.

Table 7. Constant Friction Coefficient (μ) Braking Distance

Runway –Tire μ	-40°F ▶		70°F ▶		160°F ▶	
	KC-135 system (ft)	Two-fluid system (ft)	KC-135 system (ft)	Two-fluid system (ft)	KC-135 system (ft)	Two-fluid system (ft)
.6	1,782	2,086	1,874	1,956	1,815	1,866
.5	2,235	2,688	2,602	2,544	2,572	2,466
.4	2,865	3,562	3,587	3,302	3,751	3,144
.3	4,003	5,013	5,401	5,207	5,859	4,729
.2	6,484	7,479	8,896	7,773	8,715	8,069
.1	9,957	11,717	15,050	13,537	13,440	16,523

▶ Nominal fluid and test cell ambient temperature.

Table 8. Step Friction Coefficient (μ) Braking Distance

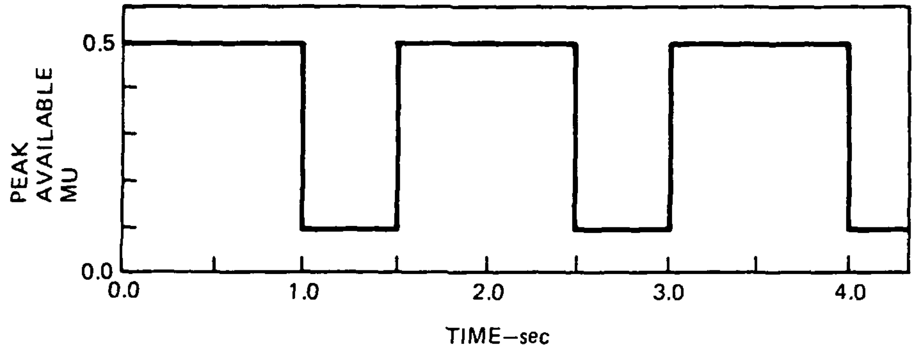
Step μ period (sec)	-40°F ▶		70°F ▶		160°F ▶	
	KC-135 system (ft)	Two-fluid system (ft)	KC-135 system (ft)	Two-fluid system (ft)	KC-135 system (ft)	Two-fluid system (ft)
1.5 ▷	5,329		5,170		3,894	
2.0		5,903		5,019		4,263

▶ Nominal fluid and test cell ambient temperature

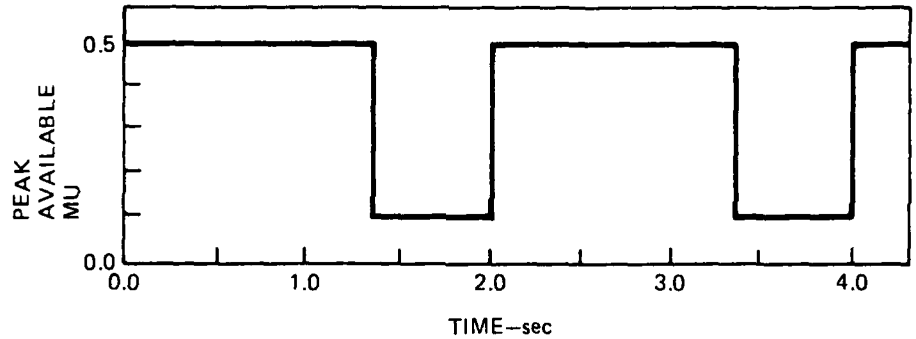
▷ Step μ periodic cycles defined in Figure 26

Max μ = 0.5

Min μ = 0.1



(a) Standard Variation of Mu



(b) Revised Variation of Mu for Two-Fluid Systems

Figure 26. Step Friction Test—Friction Coefficient Versus Time

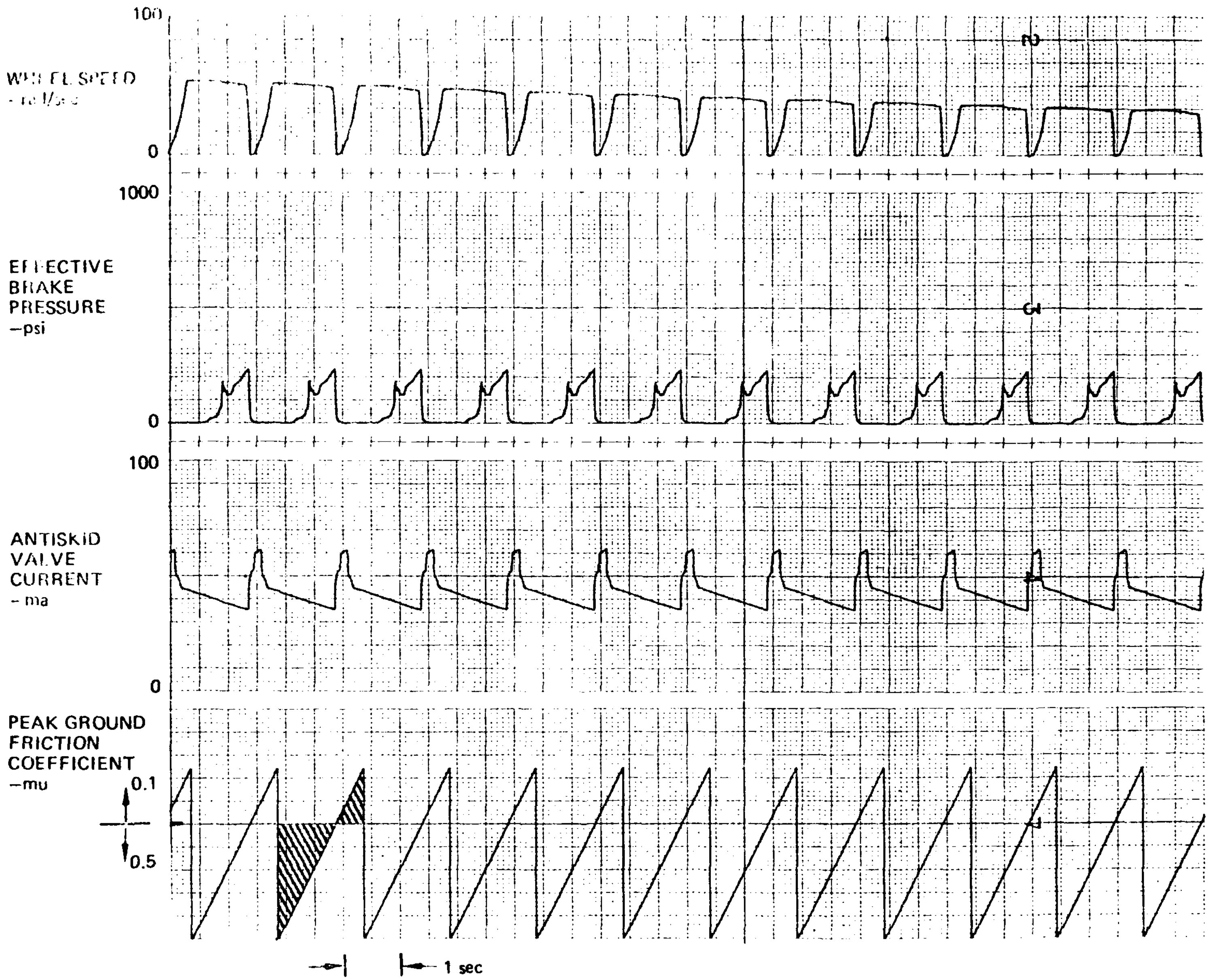


Figure 27. As-Built Brake System Step-Friction Performance at Room Temperature

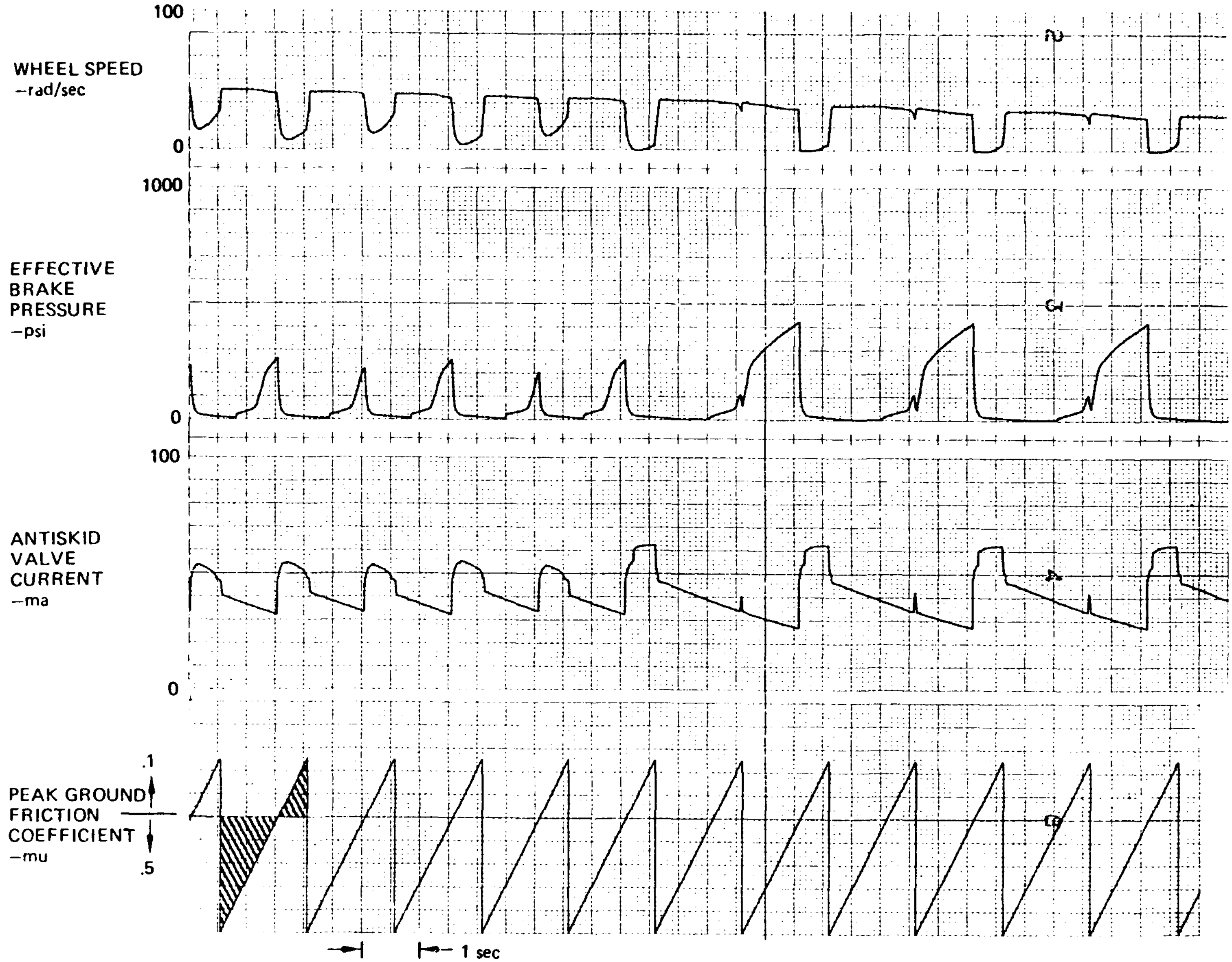


Figure 28. As-Built Brake System Step-Friction Performance at -40° F

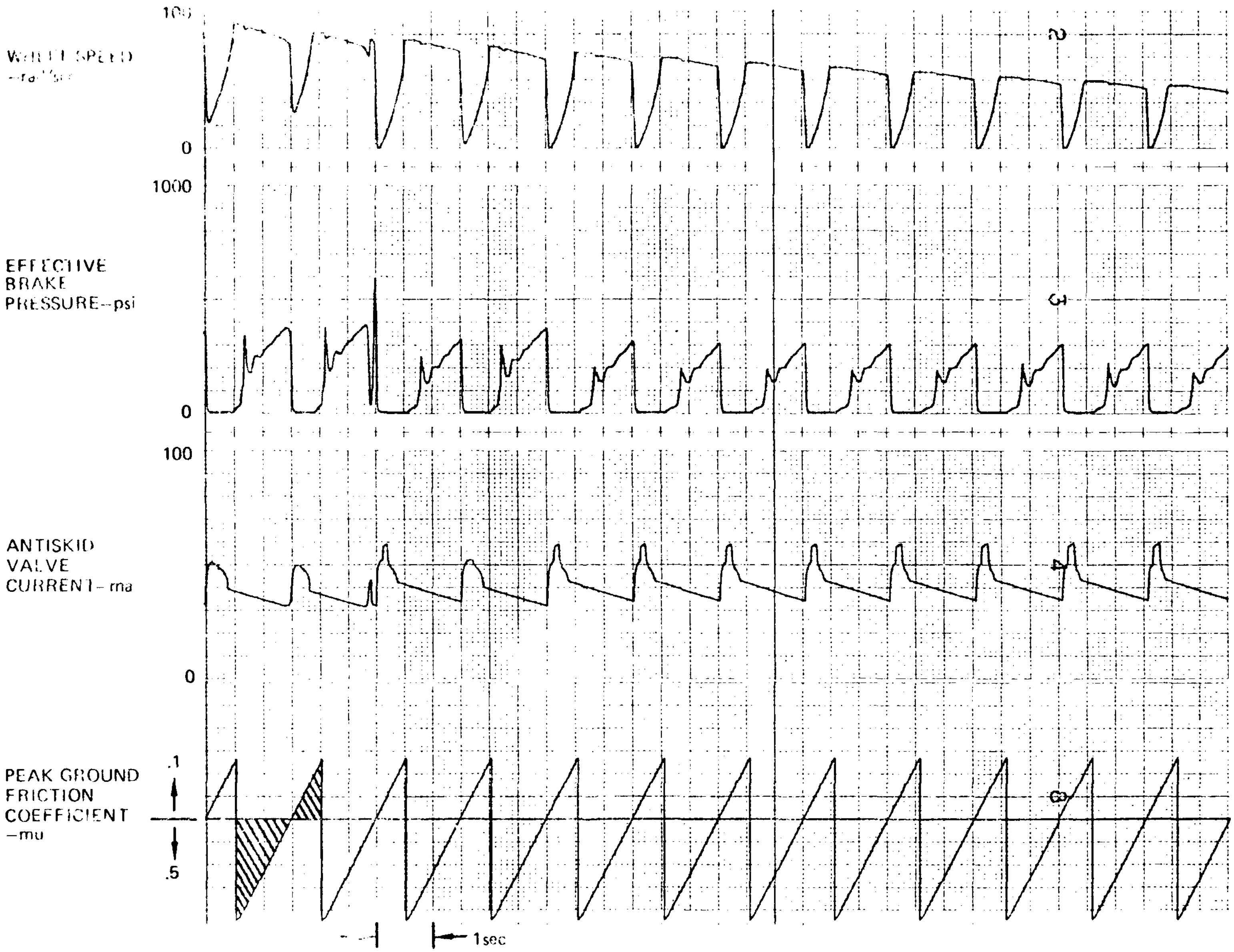


Figure 29. As-Built System Step-Friction Performance at 160° F

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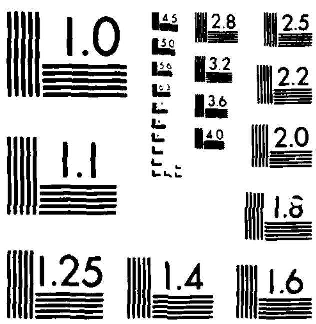

MICROCOPY RESOLUTION TEST CHART

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(5) Landing Gear Stability--The extent to which the C/KC-135 brake control system contributes to the fore and aft vibrational stability of the landing gear was evaluated by determining the minimum level of fore and aft landing gear strut damping required for stable landing gear oscillations.

During a normal braked landing, at a tire-runway friction coefficient of 0.5, the landing gear strut was made to oscillate by increasing the brake torque to 1.5 times its normal value for a short period of time. The strut damping ratio was lowered until the landing gear oscillations were undamped, the brake system unstable, or the strut damping ratio was zero. The strut damping ratio at the point of instability was recorded.

The test was performed at room temperature -40°F and 160°F. The test results are summarized in Table 9. Typical time history plots of wheel speed, brake pressure, valve current, ground force, brake torque and strut displacement at ambient temperature with normal strut damping (damping ratio equals .707) and zero damping are given in Figures 30 and 31. The strut is stable in both of these cases. The time history data for the -40°F and 160°F showed characteristics similar to the ambient temperature data.

3. FIREPROOF HYDRAULIC BRAKE SYSTEM TESTS

a. Test Rig Description--Performance testing of the FHBS was performed using a mockup of the two-fluid brake hydraulic system. This mockup was built to the design drawings as regards to tubing and hose diameter, wall thickness, length, tube bend geometry, and material. The reservoir/separator and deboost valve used in the mockup were also prepared in compliance with the flight test kit design drawings. The general arrangement of the mockup including instrumentation locations and hydraulic line length is shown in Figure 18 and a photograph of the test setup is shown in Figure 32.

Table 9. Landing Gear Stability; As-Built System

Temperature (^oF)	Fore-aft DOF strut damping ratio	Results summary
70	0.707	Strut oscillations are damped
	0.000	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; random oscillations are interpreted as skids
-40	0.707	Strut oscillations are damped
	0.000	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; oscillations are not interpreted as skids
160	0.707	Strut oscillations are damped
	0.000	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; oscillations are not interpreted as skids

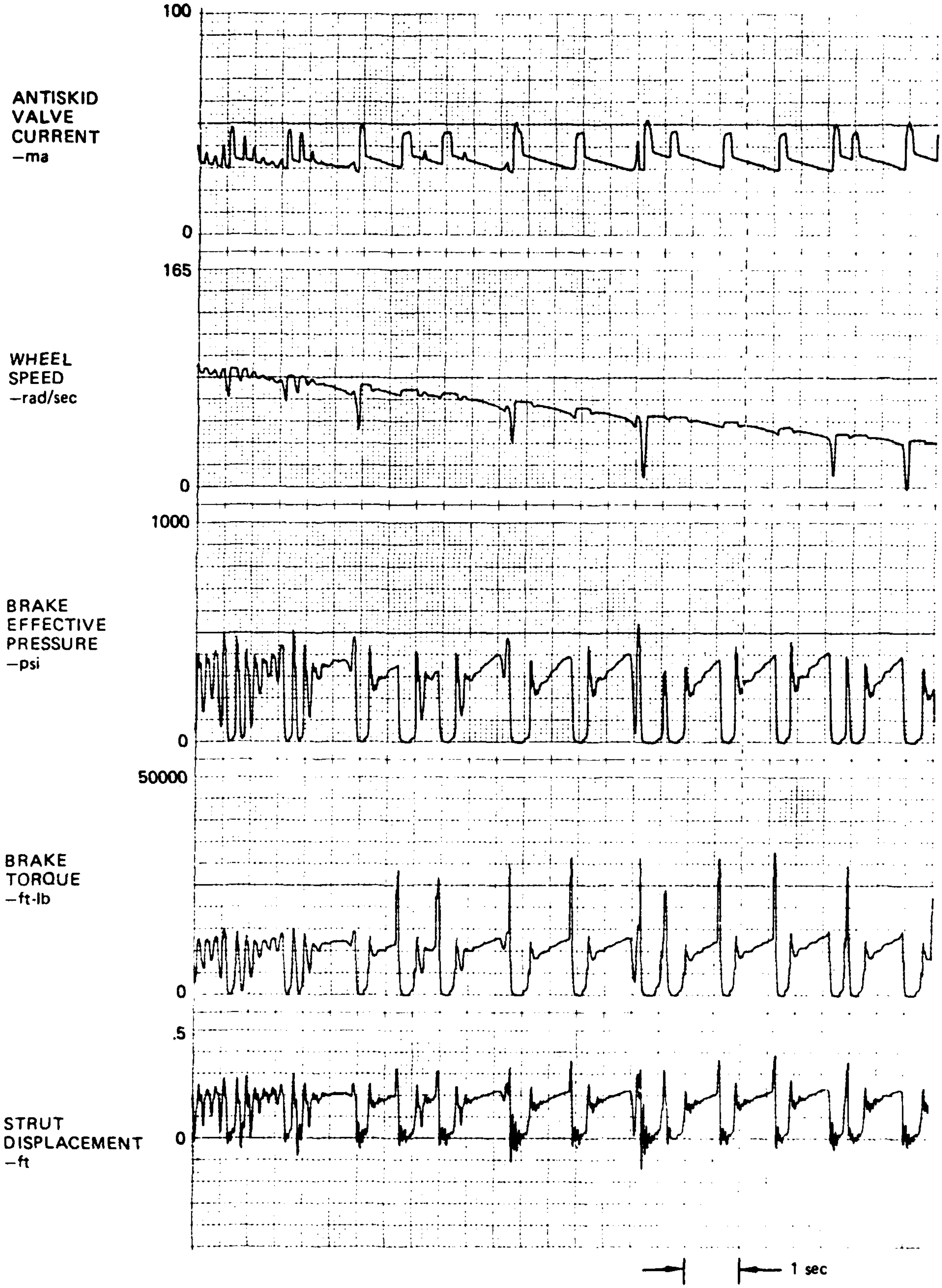

Figure 30. As-Built Brake System Stability at Room Temperature, Normal Strut Damping

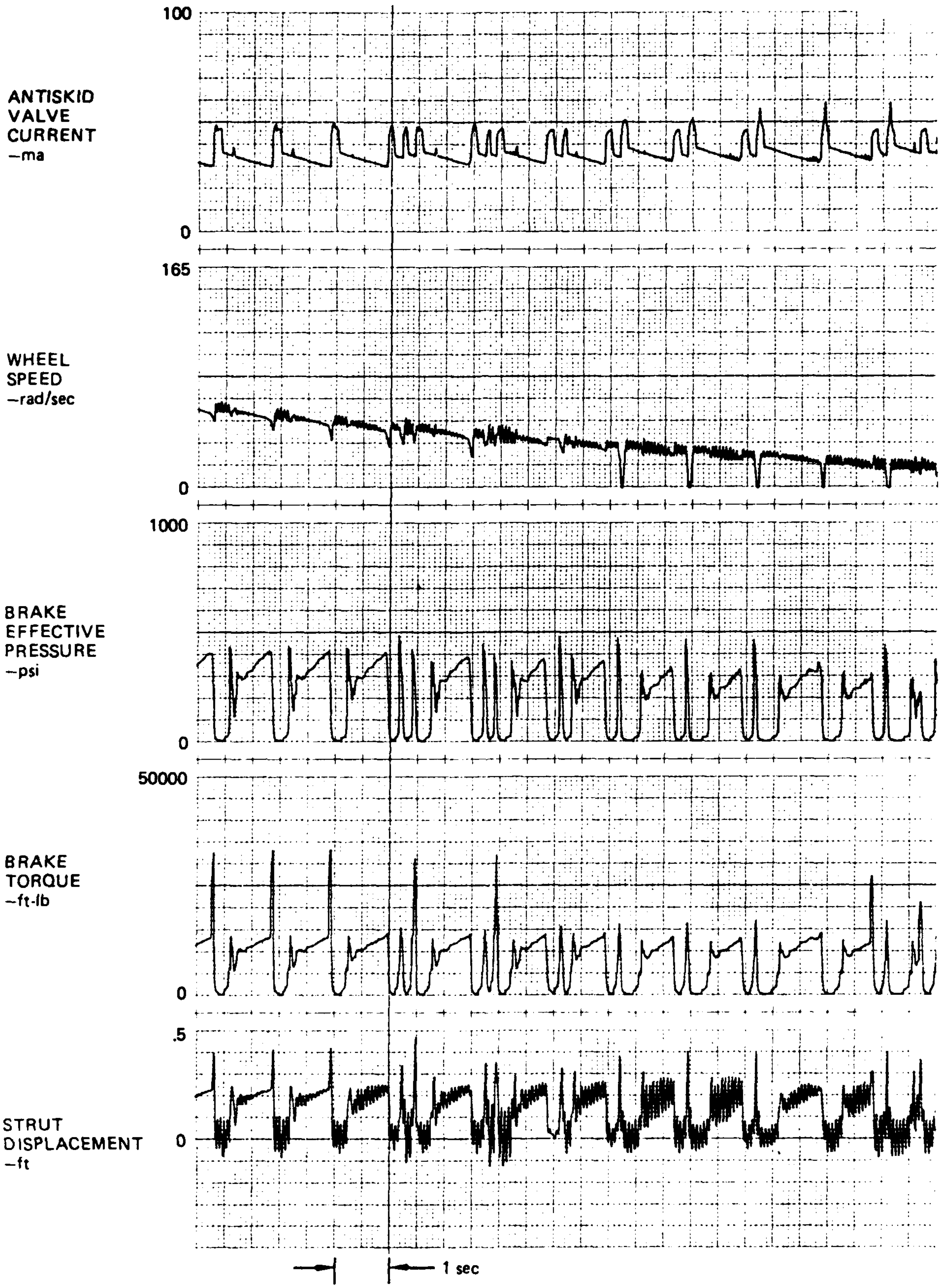

Figure 31. As-Built Brake System Stability at Room Temperature, Zero Strut Damping

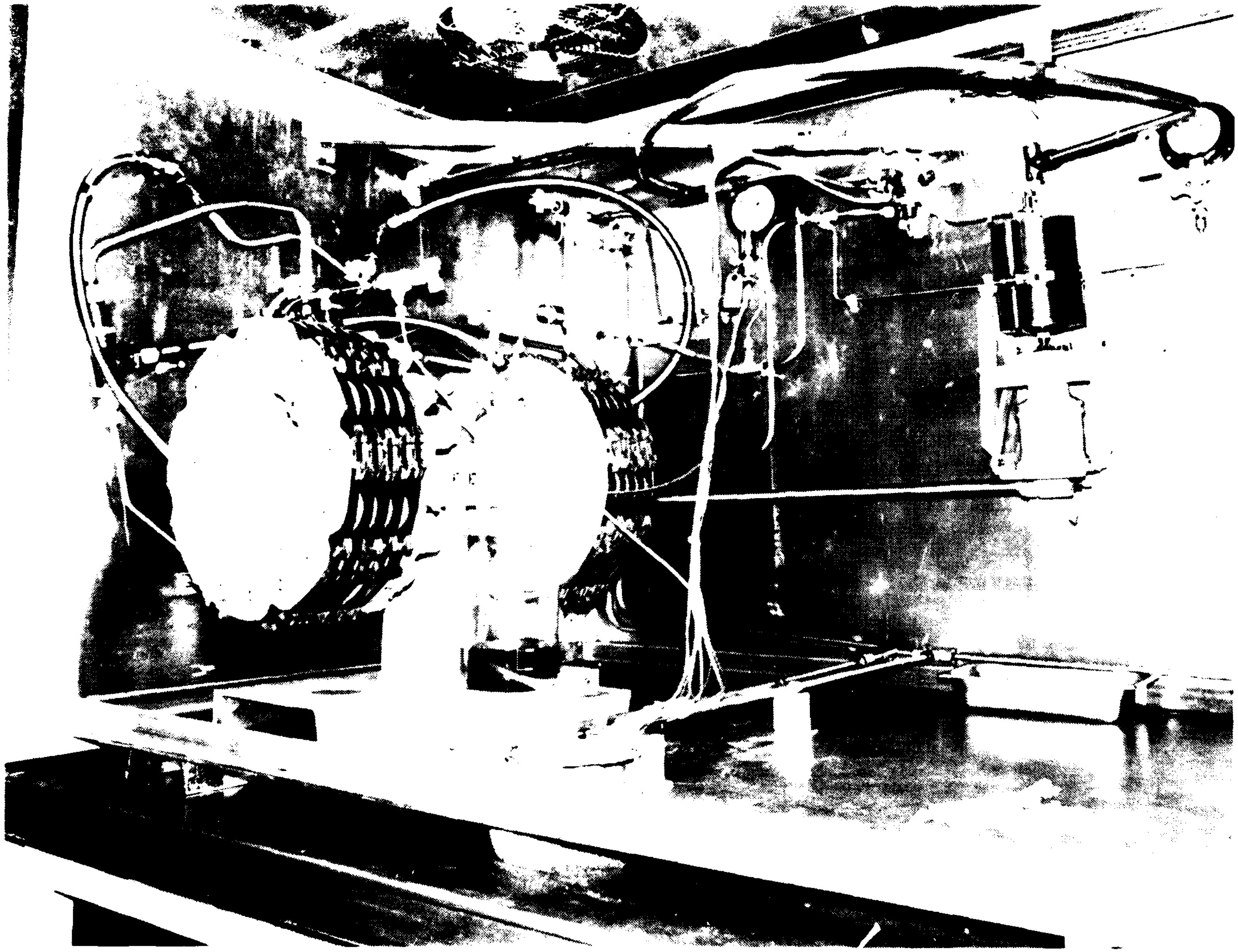

Figure 32. Two-Fluid Brake System Test Setup

b. Maintenance Demonstration Tests--The FHBS was checked for serviceability through a series of tests conducted to determine the ability of maintenance personnel to fill and bleed the hydraulic systems (MIL-H-5606 and CTFE), and perform reservoir servicing. The serviceability tests were conducted for the conditions specified in the System Flightworthiness Test Plan (Appendix C, section 3.3) and witnessed by Air Force personnel. Their comments regarding the procedures were addressed and modifications made as required. The finalized maintenance procedures were then documented in the Flight Test Demonstration Plan (Appendix E) and the Class II modification document (Reference 8).

c. One-Way Restrictor Orifice Sizing Tests--The orifice sizing tests were conducted in two phases. Phase one testing was conducted without a poppet and retainer in the one-way restrictor valve. This was done to provide a baseline response for evaluating the contribution of the restrictor check valve on system performance. For phase two, the poppet, with an orifice of appropriate diameter, and the retainer were installed.

In addition to the constant friction stopping performance test defined by the test plan for phase one, limited frequency response and step response testing was performed. The specific test conditions are shown in Tables 5 and 6. These tests were conducted at room temperature.

The step response tests were accomplished to evaluate the capability of the one-way restrictor valve orifice to control pressure overshoot on brake application and any tendency to hinder pressure decay on brake release. The frequency response data were taken for the record and future reference if required.

Phase two testing evaluated the following orifice diameters: 0.10, 0.055, 0.04, and 0.035 inch.

A comparative evaluation of the stopping performance and step response data led to choosing an 0.035 inch orifice diameter. Included in this evaluation was the stopping distance over the normal range of mu (.2 thru .5) and consideration of the damping provided by orifice over the -65°F to 160°F temperature range.

d. <u>Performance Tests</u>--After selecting the one-way restrictor orifice diameter, performance tests were conducted at room temperature, 160°F and -40°F. The ambient temperature tests were performed with a room temperature of 66 ± 3°F and a fluid temperature of 68 ± 4°F.

High temperature tests were conducted after soaking in the chamber at 162 ± 2°F for more than 13 hours. The fluid temperature was 162 ± 2°F during the testing.

Since the baseline system minimum temperature tests were conducted at -40°F, this temperature was used for the two-fluid system testing to provide directly comparable test data. Seal leakage at -40°F for the two-fluid system was very similar to the baseline system; the only noticeable leakage was at the antiskid valve face seal. This leakage stopped after commanding the servovalve at 0.5 Hz for less than one minute. The low temperature performance and intermediate temperature icing tests were performed after soaking in the chamber at -40°F for more than 12 hours. The chamber temperature remained at -39°F and the fluid temperature changed from -39°F to -36°F during the performance testing.

The dynamic response test conditions are summarized in Table 5 and the stopping performance test conditions are summarized in Table 6.

(1) <u>Frequency Response</u>--Testing was conducted on the two-fluid brake hydraulic system to determine an apparent frequency response of the two-fluid system to a sinusoidal command signal to the antiskid control valve. When using these data, the user is cautioned that a major assumption of the frequency response analysis technique, a linear system, has been violated by the use of the one-way restrictor valve; during the half of the sinusoidal command signal that applies brake pressure, the one-way restrictor valve is closed and the flow is through the 0.035 inch orifice, thereby reducing the rate of pressure increase and distorting the pressure wave downstream of the orifice. During the alternate half cycle, which releases brake pressure, the flow is through the open valve which has negligible pressure drop and pressure wave distortion. Another indication of a very nonlinear system is that when the data acquisition sample time or sample delay time is changed between frequency scans, the gain and phase shift data will have random spurious differences.

The test command signals were set as described in Section IX.2.b(1). The test conditions performed are summarized in Table 5. The response of the antiskid valve is shown by Figure D.80 in Appendix D. Likewise, Figures D.81 thru D.86 give the test results for the brake system. Figures D.87 thru D.92 give test results for the brake hydraulic system.

(2) <u>Step Response</u>--The step response tests were performed to determine the dynamic response of the two-fluid brake hydraulic system to a step change in the antiskid valve command signal. The test command signals were set as described in Section IX.2.b(2). The test conditions are given in Table 5. The response of the brake system to a step pressure change command is shown in Figures D.32 thru D.79 in Appendix D. These figures also show, for direct comparison, the step response data for the "as-built" baseline system testing.

(3) Constant Friction Stopping Performance--The stopping performance of the C/KC-135 aircraft equipped with the two-fluid fireproof brake hydraulic system on all main landing gear wheels was predicted as a function of the tire-runway friction coefficient. The procedure for conducting these tests is described in Section IX.2.b(3). The test results are given in Table 7. Typical time history plots of wheel speed, brake pressure, and antiskid current at each tire-runway friction coefficient and room temperature are given in Figures D.93 thru D.98, in Appendix D. Similar results at -40^{0}F are given in Figures D.99 thru D.104 and the 160^{0}F results are given in Figures D.105 thru D.110.

(4) Stepped Friction Performance - This test determined the adaptability of the two-fluid brake system to a step change in tire-runway friction coefficient, thereby simulating icy patches or tar strips. A secondary result is an evaluation of the influence of these simuated conditions on stopping performance.

For these tests the peak available braked landing was varied in the periodic step manner shown in Figure 26. The test plan called out the step frequency described in Figure 26(a). The stopping distance for this test condition was greater than anticipated. Examination of the system performance data, Figure 33, revealed that the hydraulic pressure was applied to the brake just as the step change of mu from 0.5 to 0.1 occurred.

Comparison of similar data for the "as-built" C/KC-135 brake system, Figure 27, to that in Figure 33, shows that the time to refill the brake cylinders and compress the retractor spring, indicated by the brake pressure increasing to 50 psi, is 0.7 seconds compared to 1.05 seconds for the two-fluid system: an increase of 0.25 seconds. The greater delay caused the pressure to be applied to the brake during the low mu portion of the cycle rather than during the high mu portion as experienced by the "as-built" system. This is a classic example of dynamic coupling where the natural frequency of the system matches the frequency of the forcing function which, in this case, is the cyclic step mu. Revising the period of the step mu cycle from 1.5 to 2.0 seconds, Figure 26(b), decoupled the forcing function from the system. For

example, comparing the test data shown by Figure 34 with that shown in Figure 33, it can be observed that the effective brake pressure rises to about 350 psi during the high-mu portion of the revised step frequency. For the standard step frequency, Figure 33, the effective brake pressure rises to only 140 psi before mu is stepped to the low value, thereby allowing a skid to be developed. For most operational situations the occurrence of a step mu will be runway distance dependent rather than time dependent as was done in this simulation. Therefore, under actual operating conditions, it is highly unlikely that a repetitive step mu condition at the system's natural frequency will be encountered.

This test was performed at room temperature, -40^{O}F, and 160^{O}F. The distance from brake application to an aircraft speed of 24 feet per second was recorded and summarized in Table 8. Typical time history plots of wheel speed, brake pressure, antiskid valve current, and the peak runway friction coefficient at the three test temperatures are given in Figure 34, 35, and 36.

(5) Landing Gear Stability--The extent to which the C/KC-135 brake control system, combined with two-fluid hydraulic system, contributes to the fore and aft vibrational stability of the landing gear was evaluated by determining the minimum level of fore and aft landing gear strut damping required for stable landing gear oscillations.

During a normal braked landing (at a runway friction coefficient of 0.5) the landing gear strut was made to oscillate by increasing the brake torque to 1.5 times its normal value for a short period of time. The strut damping ratio was lowered until the landing gear oscillations were undamped, the brake system unstable, or the strut damping ratio was zero. The strut damping ratio at the point of instability was recorded.

The test was performed at room temperature, -40^{O}F and + 160^{O}F. The test results are given in Table 10. Typical time history plots of wheelspeed, brake pressure, valve current, ground force, brake torque and strut displacement at ambient temperature with normal strut damping (damping ratio equals .707), zero damping and a 0.1 damping ratio are given in Figures 37,

Figure 33. Two-Fluid Brake System Step-Friction Performance at Room Temperature, Standard Step Frequency

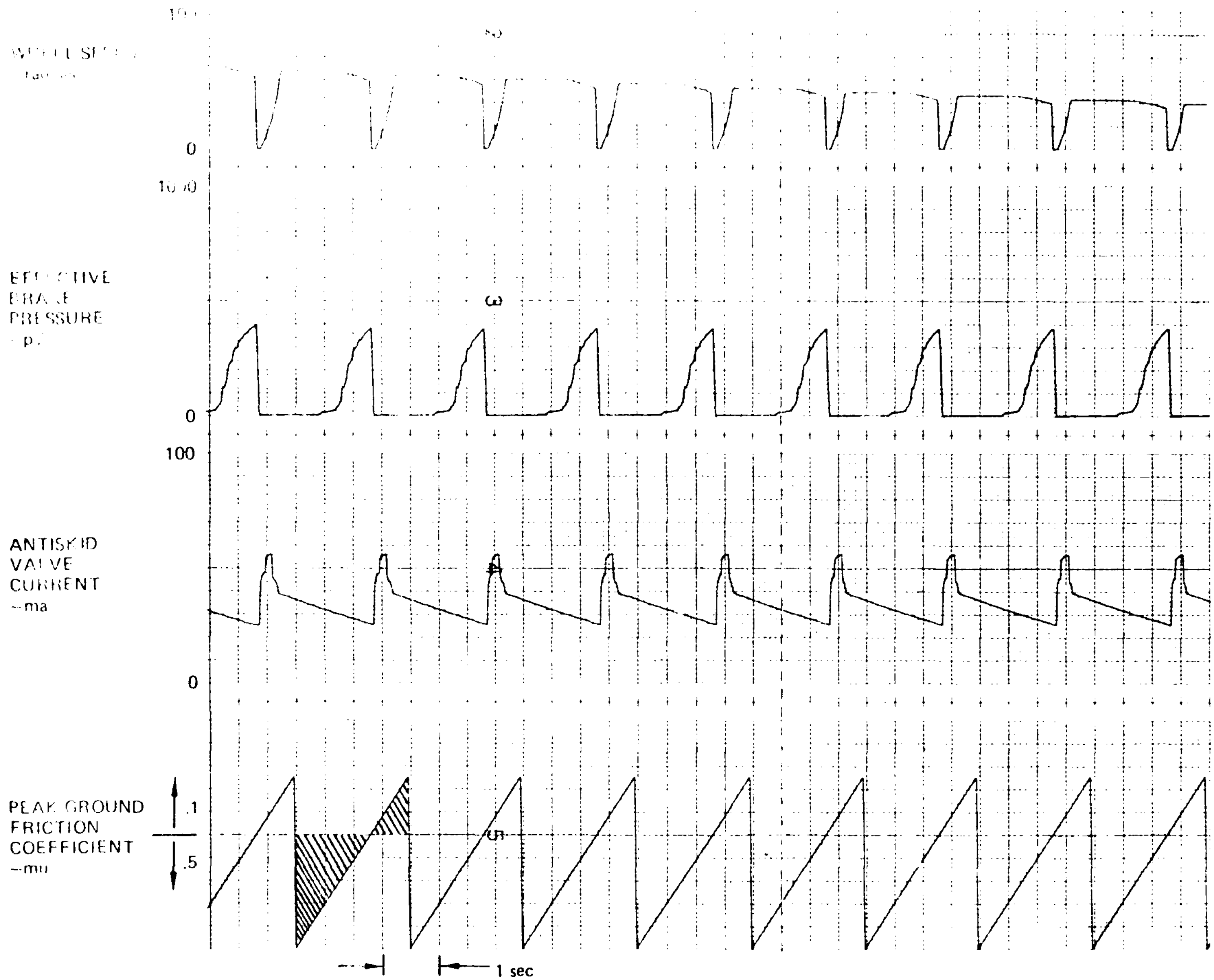

Figure 34. Two Fluid Brake System Step-Friction Performance at Room Temperature, Revised Step Frequency

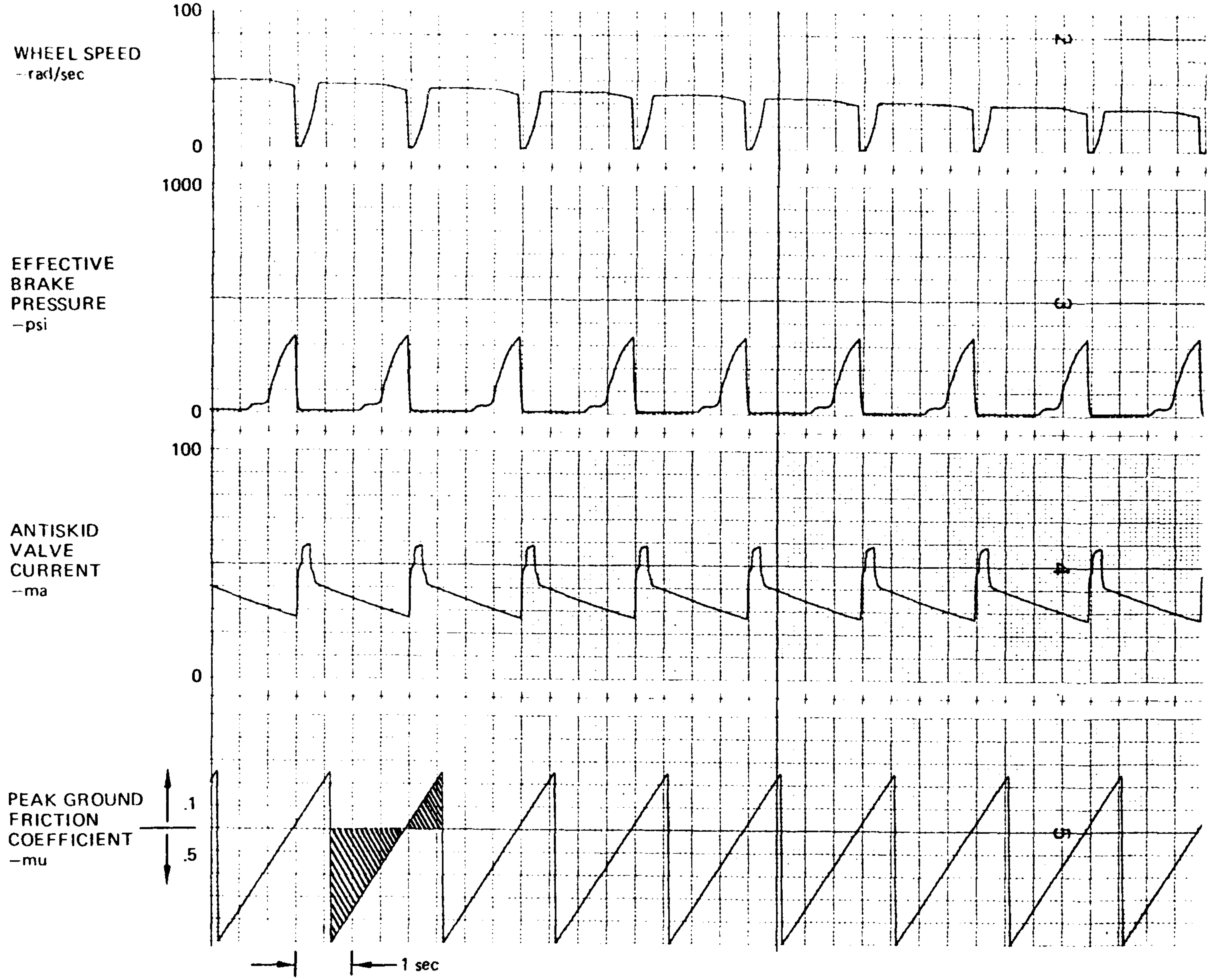

Figure 35. Two-Fluid Brake System Step-Friction Performance at -40° F

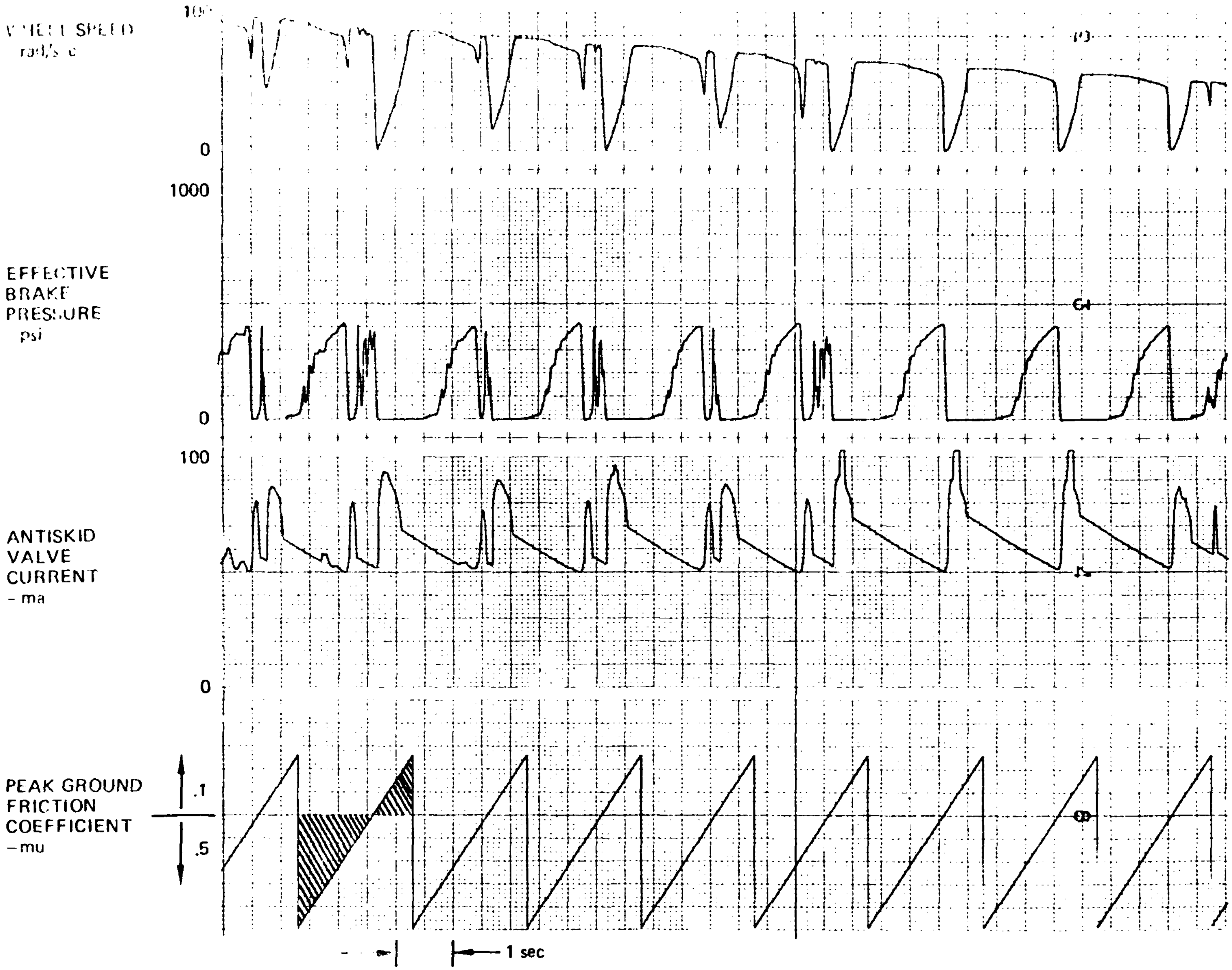

Figure 36. Two-Fluid Brake System Step-Friction Performamce at 160° F

Table 10. Landing Gear Stability; Two-Fluid System

Temperature (°F)	Fore-aft DOF strut damping ratio	Results summary
70	0.707	Strut oscillations are damped
	0.000	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; random oscillations are interpreted as skids
-40	0.707	Strut oscillations are damped
	0.100	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; random oscillations are interpreted as skids
160	0.707	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; oscillations are not interpreted as skids
	0.200	Strut oscillations are damped; strut oscillation superimposes ripple on wheel speed; random oscillations are interpreted as skids

38, and 39. The strut was stable in the normal and 0.1 damping ratio cases. For zero damping, Figure 38, the strut displacement after brake pressure reduction was large enough to be interpreted as a skid thereby causing a pressure release. The strut displacement data shown in Figure 38 indicated some strut displacement ringing. When the damping ratio was increased to 0.1, Figure 39, the strut displacement oscillations are sufficiently reduced so that the antiskid controller did not interpret this activity as a skid.

(6) Intermediate Temperature Icing Test--This test was conducted immediately on completion of all other -40°F tests. The system was rapidly warmed to 160°F by changing the environmental chamber temperature set point to 165°F and opening the chamber door.

While the temperature was increasing, system frequency response tests were conducted at -35°F, 5°F, 25°F, 60°F, 100°F, 130°F, and 155°F. While the temperature was less than 25°F, the FHBS test rig was sprayed with water and the motion of the reservoir/separator rod observed for evidence of sticking and the rod seal checked for fluid leakage. The rod moved freely when the reservoir/separator was otherwise coated with ice. There was no evidence of rod seal leakage.

4. COMPARATIVE ANALYSIS

This comparative analysis will address the verification of the brake hydraulic system frequency response mathematical model and an assessment of the performance of the two-fluid FHBS versus the "as-built" C/KC-135 brake system.

a. Frequency Response Model Verification--Frequency response models of the brake hydraulic system were prepared using the USAF developed Hydraulic System Frequency Response (HSFR) computer program. As reported in detail in Appendix A, the modeling technique was verified using test data from the previous C/KC-135 brake system mockup. These math models were then revised to represent the "as-built" C/KC-135 brake hydraulic system. These models were further revised to represent the various two-fluid FHBS configurations under study.

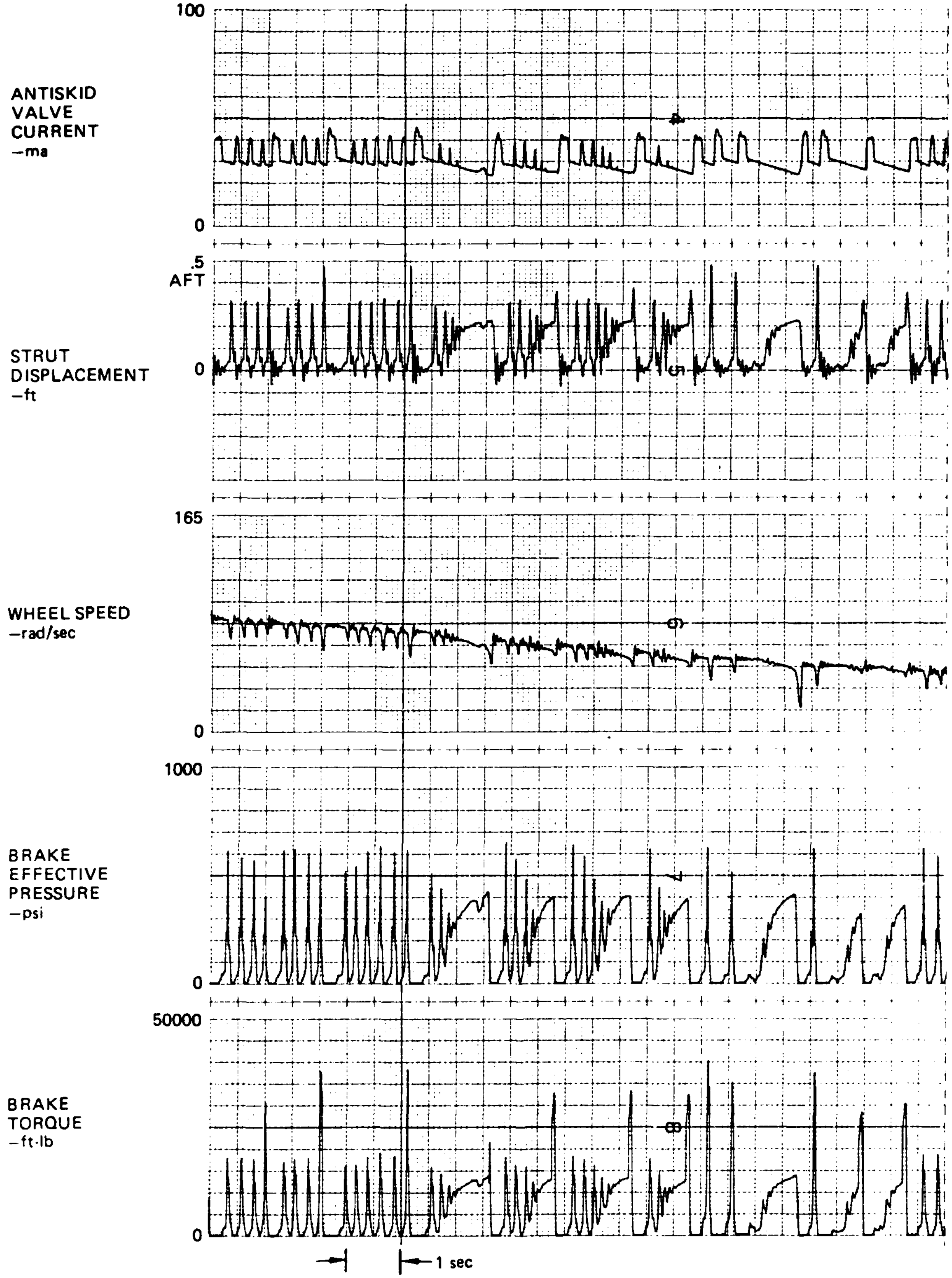

Figure 37. Two-Fluid Brake System Stability at Room Temperature, Normal Strut Damping

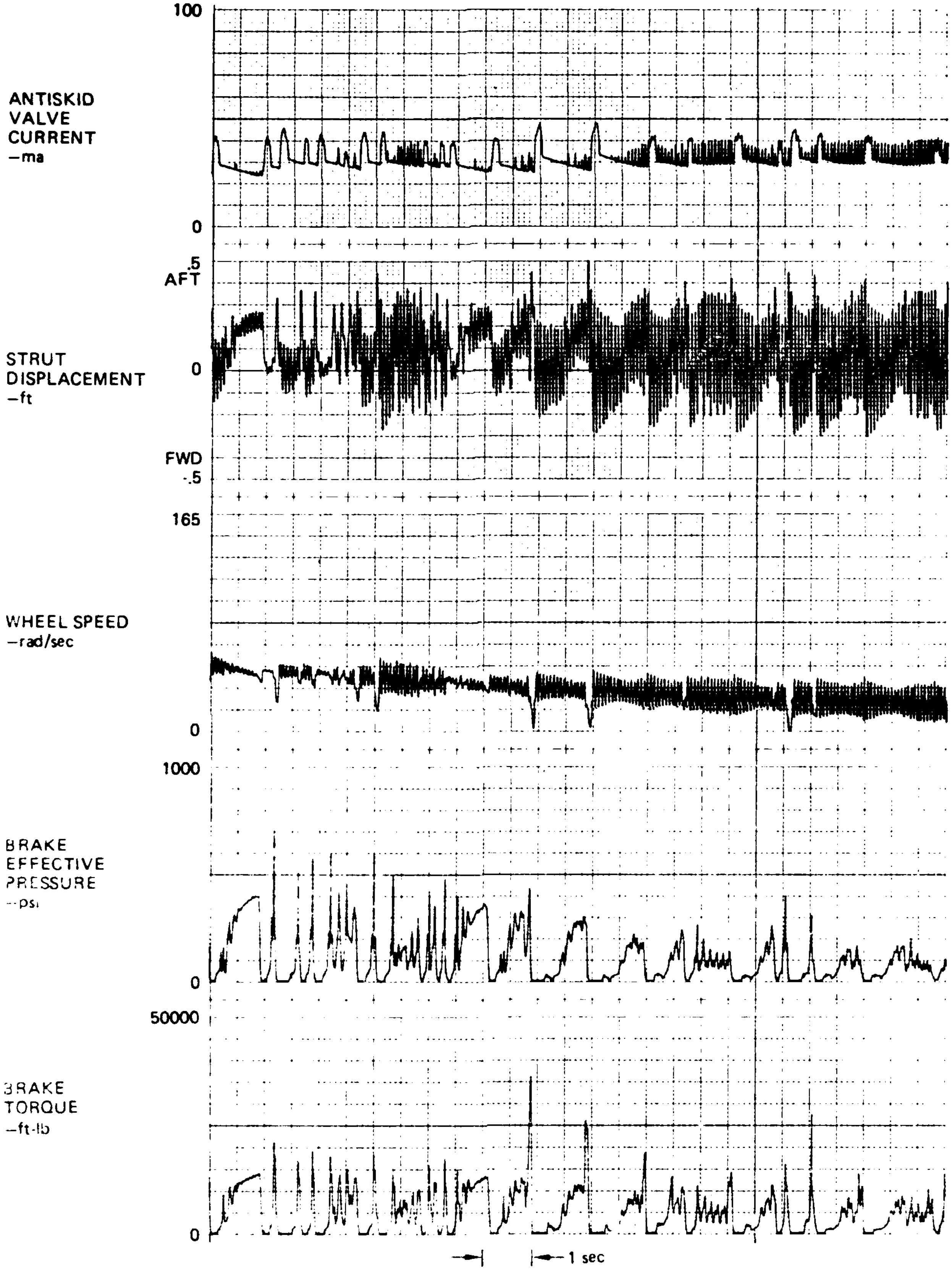

Figure 38. Two-Fluid Brake System Stability at Room Temperature, Zero Strut Damping

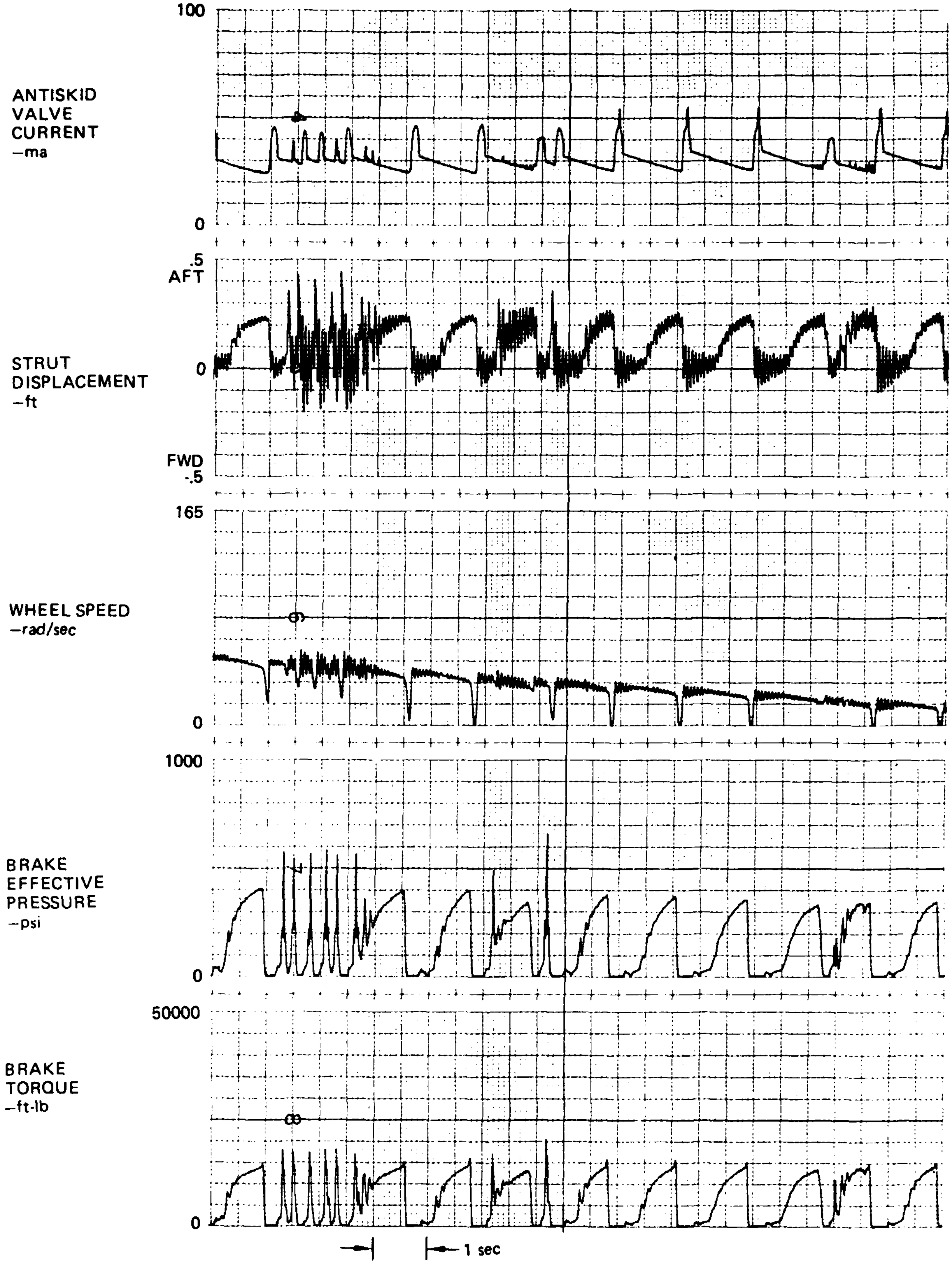

Figure 39. Two-Fluid Brake System Stability at Room Temperature, Strut Damping Ratio = 0.1

With this approach, the math models of the two-fluid system are two revisions away from models that were verified with test data. Therefore, frequency response data from the "as-built" C/KC-135 system baseline testing was used to validate the HSFR models.

The analysis and test data are compared in Figure 40. These data show that the response of the math model agrees with the response of the actual system to within 0.5 dB for peak gain and within 1.5 Hertz for the break frequency (-90° phase shift). Due to the good correlation of the analytic data with the test data, no adjustment of the model parameters was recommended for this program.

b. Stopping Distance Comparison--An objective of the FHBS program was that the two-fluid fireproof brake system design shall exhibit braking performance equivalency compared to the original brake system. One demonstration of equivalent performance was accomplished by comparing the constant friction coefficient (mu) stopping performance for each system that was predicted by the hybrid simulation of C/KC-135 brake system.

Results of the stopping performance testing for both systems, the "as-built" and the two-fluid systems, are summarized in Table 7. These data show, with one exception, that for any specific nominal value of tire-runway friction coefficient (mu = 0.2 to 0.5) the stopping distance of the two-fluid system for any temperature was less than that of the "as-built" system at the worst-case temperature, i.e., the temperature with the greatest stopping distance. The condition of exception is mu = 0.5 at -40°F, where the two-fluid system distance exceeds the "as-built" system maximum distance, at 70°F, by 3.3%.

Though the constant mu stopping test covered the range mu = 0.1 to 0.6, the nominal range experienced in operation is 0.2 to 0.5 for the following reasons:

(1) The mu = 0.6 represents a seldom achieved maximum value where the runway and tire conditions are perfect.

(2) The mu = 0.1 represents a runway covered by a continuous sheet of ice.

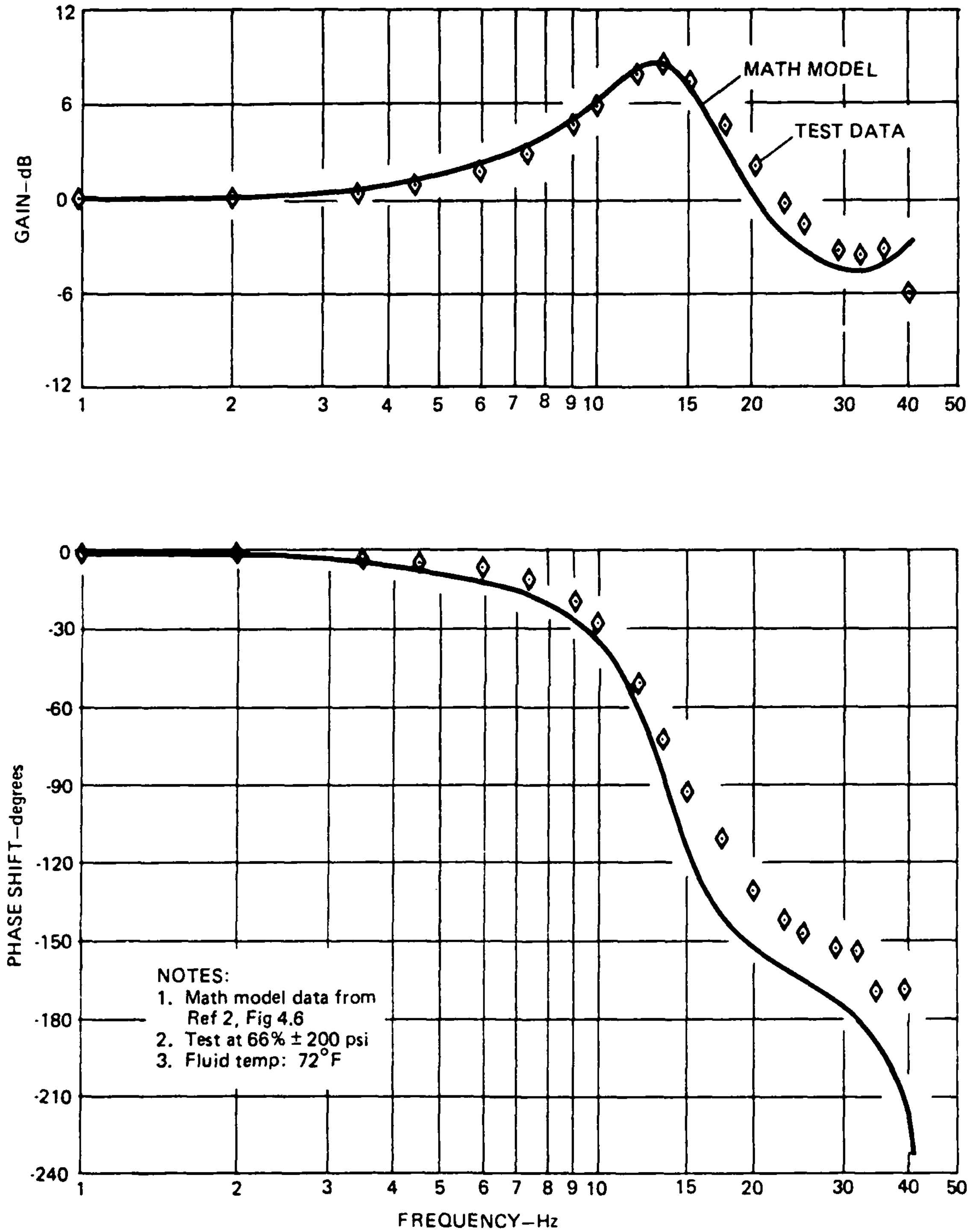

Figure 40. Correlation of Analytic and Test Data for As-built KC-135 Brake Hydraulic System

Another factor to consider when evaluating these data is that the predicted stopping distances were calculated with the assumption that all four antiskid wheel pair circuits were modified. For the planned flight test program, only one antiskid wheel pair is to be converted to the two-fluid system. Therefore, as a first approximation, it is assumed that the change in stopping distance shown for the flight test configuration would be 25% of the difference in the values shown in Table 7.

c. Step Friction Coefficient Performance--The second demonstration of equivalent performance to the "as-built" system is the step mu test. The purpose of this test was to demonstrate the capability of the antiskid system to adapt to a step change in tire-runway friction coefficient. The step change from mu = 0.5 to 0.1 represented encountering wet tar strips or icy patches on an otherwise dry runway. Figures 34, 35, and 36 show that the response of the two-fluid system is equal to the "as-built" system response, Figures 27, 28, and 29, at each test temperature. A secondary purpose of this test was to demonstrate the stopping performance while encountering step changes of mu. These data are shown in Table 8. A quantitative comparison of these results can not be done due to the revision of the step mu frequency that was made to eliminate coupling between the forcing function and the two-fluid brake system. Additional details of the system dynamic response to step friction conditions is discussed in Section IX.3.d(4).

X. RELIABILITY/MAINTAINABILITY STUDY

The reliability/maintainability study was completed in two phases; preliminary and final studies. The preliminary reliability/maintainability study evaluated the various FHBS candidates for the CTFE replenishment system trade study. The results of those studies were presented in the FHBS Interim Report (Reference 4). The final reliability/maintainability study that follows was conducted on the final FHBS design. Recommended procedures and designs were integrated into the Class II Modification Document (Part II), Reference 8, paragraphs 2.4 and 2.8.

The final analysis was conducted to evaluate the reliability/maintainability impact on the C/KC-135 brake system when additional components are added to create the two-fluid Fireproof Hydraulic Brake System. The reliability/maintainability assessment of the FHBS is based upon data collected during 399,496 C/KC-135 flight hours. It was determined that inherent reliability and maintainability would be affected due to the added components required for the FHBS. The additional components present no reliability/maintainability degradation sufficient to override the obvious advantage of a fireproof hydraulic brake system. This analysis considered the following factors: 1) the affect of the two-fluid system and component hardware design on the failure rate, maintenance manhour per flight hour, maintenance task frequency and reliability of the C/KC-135 brake system; 2) possibility of servicing errors that could compromise reliability/ maintainability; and 3) additional support equipment requirements of the FHBS. It is noted that all components used in the FHBS are original C/KC-135 components with following exceptions:

1) Deboost Valve is an original C/KC-135 design modified with PNF seals that are compatible with CTFE fluid. No impact on valve reliability is expected as the new seals are assumed to be equally as reliable as the original Buna-N seals.

2) Reservoir/Separator is a new component designed by Boeing. Reliability estimates are provided.

3) Fill and Bleed valves were provided at the FHBS at the reservoir/separator to fill and bleed the CTFE fluid. The valves are military standard parts for which reliability factors are calculated within overall system reliability.

4) Lines and fittings in the FHBS are assumed to have the same reliability/maintainability characteristics as existing C/KC-135 equipment.

Failure rates and maintenance manhour calculations, presented in Table 11, include the attaching parts for each component. The FHBS reliability/maintainability analysis is presented in the following discussion.

Inherent reliability of the C/KC-135 brake system was slightly degraded by the additional FHBS components and hardware. Design of the FHBS system requires the removal of two existing hydraulic fuses, which offsets the impact of adding the reservoir/separator to the system. Elimination of the two hydraulic fuses will provide a slight decrease in overall system failure rate. The addition of the CTFE reservoir/separator was required to separate the two fluids and provide a storage reservoir for the CTFE fluid. Reservoir/separator reliability was calculated using data from a comparable C/KC-135 component. The addition of the fill valve and bleed valve was calculated as attaching parts to the reservoir/separator. The predicted failure rate of the FHBS is .0730 failures per flight hour as compared to a failure rate of .0715 for the existing C/KC-135 brake system. System reliability calculations are based on the following equation:

$$R = e^{-\lambda t}$$

where:

λ = failures per flight hour

t = sortie length in hours = 4 hours

The calculation includes all failures that required maintenance to return the system to a mission capable status.

TABLE 11 - RELIABILITY/MAINTAINABILITY ASSESSMENT

	FAILURES PER FLIGHT HOUR	RELIABILITY	TASK PER FLIGHT HR	MMH/FH	MEAN TIME TO REPAIR (MMTR)
EXISTING C/KC-135 BRAKE SYSTEM	.0715	.7510	.0588	.2640	1.10
REMOVED FUSES	.000051	.9997	.000127	.0009	.96
ADDED: RESERVOIR/ SEPARATOR	.00166	.9936	.000637	.0028	2.24
FIREPROOF HYDRAULIC BRAKE SYSTEM (FHBS)	.0730	.7467	.0589	.2444	1.67

Maintainability of the FHBS considered the following parameters: 1) mean time to repair (MTTR); 2) maintenance manhours per flight hour (MMH/FH); 3) relative ease of maintenance as compared to the existing system; 4) and the impact of possible mixed fluids in the systems. The location of the reservoir/separator and the deboost valve in the aft section of the wheel well assures accessibility for ease of servicing and maintenance. To reduce the possibility of fluid mixing during servicing two steps were taken; 1) the reservoir/separator and CTFE servicing valve are plainly marked to indicate the presence of CTFE fluid in the system. 2) the CTFE servicing valve is unique to the brake system and is not compatible with the charging fitting on the MIL-H-5606 servicing cart.

The MTTR and MMH/FH calculations are included in Table 11.

Pre/post flight inspection requirements for the FHBS are considered the same as those required for the existing C/KC-135 brake system with the following additions:

(1) Inspect CTFE Reservoir/Separator fluid quantity gauge to insure reservoir is serviced to 80% capacity.

(2) Inspect CTFE reservoir/separator for excessive leakage from the seal vent (weep) holes. NOTE: Wetness from seepage is allowed.

The procedures for filling and bleeding the brakes in the CTFE system are the same as existing C/KC-135. Specific bleeding and filling procedures for the reservoir/separator are contained in Appendix E and Reference 8. There are no special inspections or maintenance requirements for the system once installed on the test aircraft.

A CTFE fluid servicing cart with a special charging fitting to service the reservoir/separator CTFE fluid was required as support equipment.

XI. SYSTEM HAZARD ANALYSIS

The FHBS safety analysis constituted formal documentation for the two phases of the FHBS program. The initial phase required a Preliminary Hazard Analysis (PHA) of the prime candidate FHBS following the CTFE replenishment system trade study. The PHA, Reference 3, depicted those system/subsystem designs within the FHBS in terms of potential hazard to the aircraft. These hazards were quantified and changes recommended to reduce the hazard(s).

The final phase, reported in two formal documents, analyzed the safety aspects in terms of hazard to aircraft, and hazard to crew and maintenance personnel. The System/Subsystem Hazard Analysis (SSHA), Reference 6, quantified the hazardous conditions arising from all possible single failures, and as required, secondary failures. Failure detection and effects were detailed, and procedures specified that would allow safe operation of the aircraft following those failures. The Operating and Support Hazard Analysis (OSHA), Reference 7, was performed to identify and control hazards, and to determine safety requirements for personnel, procedures and equipment used during FHBS kit installation, maintenance, testing and operation for all phases of intended use. Potential hazards to the system(s) that may be induced by maintenance personnel were also examined and documented.

XII. FLIGHT TEST DEMONSTRATION PROCEDURE

A Boeing recommended FHBS flight test demonstration procedure (Appendix E) was developed and approved by the Air Force. The procedure denoted data required to demonstrate the FHBS concept and to verify equivalent stopping performance of the FHBS to the existing C/KC-135 brake system. The procedure included a detail flight test plan, recommended instrumentation/recordings, data reduction description, test article description and FHBS installation and maintenance instructions.

XIII. CLASS II MODIFICATION DESIGN DATA (PART II)

The Class II Modification Design Data (Part II) document (Reference 8) provided the final FHBS design data including detail, assembly and installation drawings; stress and weight and balance analyses; component and system flightworthiness test data; modification and demodification procedures; and airworthiness certification. The FHBS modification of a C/KC-135 aircraft is to be accomplished per Boeing drawing 180-59850 - FHBS Installation (Top Kit Drawing). A list of drawings for the kit is provided by Table 12.

The FHBS modification document contained a narrative description of the modification including detail descriptions of the new components, instrumentation interfaces, step-by-step kit installation procedures, a wheel well clearance drawing, an inboard and plan view profiles showing FHBS component location(s), CTFE fluid fill and bleed procedure, a modified MIL-H-5606 fluid fill and bleed procedure, stress analyses of the reservoir/separator and the installation bracketry, a weight and balance summary, FHBS maintenance and inspection instructions, a list of all FHBS unique drawings, component and system flightworthiness test results, and a statement of FHBS flightworthiness certification.

TABLE 12 FLIGHT TEST KIT DRAWINGS

DRAWING NUMBER	TITLE
180-59836	RESERVOIR/SEPARATOR DETAILS-FHBS
180-59837	RESERVOIR/SEPARATOR ASSY-FHBS
180-59838	DEBOOST VALVE ASSY-FHBS
180-59839	VALVE ASSY-RESTRICTER/CHECK
180-59840	ADAPTER-RESTRICTER/CHECK VALVE
180-59841	TEE-DEBOOST/FILL VALVE
180-59842	SPACER-GAUGE, FLUID LEVEL
180-59843	VALVE-FHBS FILL AND BLEED
180-59844	VALVE-RELIEF, FHBS
180-59845	BRAKE ASSY-FHBS
180-59846	NAMEPLATE-CTFE, FHBS
180-59847	SPACER BRACKET, FHBS
180-59848	TUBE ASSY - HYDRAULIC BRAKE PRESSURE, FHBS
180-59849	TUBE ASSY - HYDRAULIC BRAKE PRESSURE, FHBS
180-59850	BRAKE SYSTEM INSTL-HYDRAULIC, FIREPROOF (TOP KIT DRAWING)
180-59851	BRACKET DETAILS-FIREPROOF HYDRAULIC SYSTEM (KIT)
180-59852	BRACKET DETAILS-FIREPROOF HYDRAULIC BRAKE SYSTEM
180-59853	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59854	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59855	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59856	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59857	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59858	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59859	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59860	TUBE ASSY-HYDRAULIC BRAKE PRESSURE, FHBS
180-59992	PLATE-HOLE COVER
180-59993	RESTORATION BRAKE SYSTEM INSTL-HYDRAULIC, FIREPROOF
180-59994	WASHER-RESERVOIR/SEPARATOR CLAMP
180-59996	DELETIONS BMAC W84-302
180-59997	DELETIONS BMAC W84-302
180-59998	CLAMP-RESERVOIR/SEPARATOR, FHBS
180-59999	SPACER-FILTER RETAINER, FHBS

XIV. CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The two-fluid brake system was determined to be feasible and has shown performance equivalency to the existing C/KC-135 braking system. FHBS design and kit hardware has been shown to be flightworthy through a series of analyses and tests. CTFE/AO-2 fluid and PNF seals were determined to be satisfactory in all respects.

2. RECOMMENDATIONS

The FHBS has been shown to be flightworthy and the performance equivalent to the existing C/KC-135 brake system; therefore, the FHBS is recommended for installation and test on a flight test aircraft.

A two-fluid brake system should be considered a viable approach for reducing fire hazard on existing and new aircraft. The FHBS utilizing the reservoir/separator concept is a low risk/low cost alternative achieving a significant reduction in brake and wheel well related hydraulic fires. An FHBS design is adaptable for retrofitting onto nearly every aircraft in the Air Force inventory.

For irreplaceable aircraft, (aircraft out of production such as the C/KC-135, B-52, etc.) an FHBS can provide lower mortality rates, therefore allowing an increased service life for the aircraft type. Increased service life adds up to lower, replacement aircraft costs.

REFERENCES

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2. AFWAL-TR-81-2080, "Fireproof Brake Hydraulic System", S. M. Warren and J. R. Kilner, Boeing Military Airplane Co., September 1981.

3. D500-10189-1, Rev. C, "Preliminary Hazard Analysis, Fireproof Hydraulic Brake System Design," Boeing Military Airplane Co., April 1984.

4. D500-10401-1, Rev. C, "Fireproof Hydraulic Brake System Class II Modification Preliminary Design Data (Part 1)," Boeing Military Airplane Co., February 1985.

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8. D500-10401-2, Rev. B, "Fireproof Hydraulic Brake System Class II Modification Design Data (Part II)," Boeing Military Airplane Company, August 1985.

9. AFAPL-TR-76-43 Volume III, "Aircraft Hydraulic Systems Dynamic Analysis, Volume III Frequency Response (HSFR) Computer Program User Manual", McDonnell Aircraft Co., February 1977.

10. AFAPL-TR-76-43 Volume IV, "Aircraft Hydraulic Systems Dynamic Analysis, Volume IV Frequency Response (HSFR) Computer Program Technical Description", McDonnell Aircraft Co., February 1977.

11. AFWAL-TR-80-2111, "Design Guide for Aircraft Hydraulic Systems and Components for Use with Chlorotrifluoroethylene Nonflammable Hydraulic Fluids", Boeing Military Airplane Company, March 1982.

12. "Hydraulic and Pneumatic Power and Control", F. D. Yeaple, McGraw-Hill, 1966.

13. D-16046, "Vibration Test Requirements for Items of Equipment Installed in Model KC-135 Airplanes", The Boeing Company, Revision dated 23 May 1960.

LIST OF ABBREVIATIONS AND SYMBOLS

AND	Army - Navy Aeronautical Design Standard
AFWAL	Air Force Wright Aeronautical Laboratory
BMAC	Boeing Military Airplane Company
CDRL	Contract Data Requirements List
cg	Center of Gravity
CRES	Corrosion Resistant Steel
CTFE	Chlorotrifluoroethylene
EDM	Electro-Discharge Machining
F	Fahrenheit, Degrees
FHBS	Fireproof Hydraulic Brake System
g	Acceleration in Multiples of Gravity
HSFR	Hydraulic System Frequency Response
HYBCOL	Hybrid Brake Control Laboratory
I	Inertia
ILS	Integrated Logistics Support
m	Mass
MMH/FH	Maintenance Manhours/Flight Hour
MTTR	Mean time to Repair
OSHA	Operating and Support Hazard Analysis
PHA	Preliminary Hazards Analysis
PNF	Phosphonitrilic Fluoroelastomer
PTFE	Polytetrfluoroethylene
R	Reliability
SAE	Society of Automotive Engineers
SSHA	Subsystem/System Hazard Analysis
t	Time
TFE	Tetrafluoroethylene
v	Velocity
λ	Failures Per Flight Hour
μ	Coefficient of Friction

APPENDIX A

FREQUENCY RESPONSE ANALYSIS - TASK 2

This appendix includes in total the brake system frequency response analysis previously reported in the FHBS interim report, Reference 5.

The page, figure, table, and reference numbers have been changed from those in the document previously delivered to the USAF to be compatible with the format of this report.

A.0 FREQUENCY RESPONSE ANALYSIS-TASK 2

A.1 Summary of Task 2

A hydraulic system frequency response analysis of the FHBS baseline and alternate(s) design concepts has been accomplished. The objectives of this analysis were: (1) to predict the frequency response of the candidate system designs and compare the results with the predicted response of the "as-built" KC-135 system as regards to brake antiskid performance, and (2) to use the frequency response analytical models during the Task 1-FHBS design phase to evaluate the impact of configuration and fluid property changes on system response. The objectives were accomplished.

This study used the USAF-developed Hydraulic System Frequency Response (HSFR) computer program which was previously modified as described in Reference 2. In summary, the modifications to the HSFR program included: (1) addition of a fluid separation piston component; e.g., deboost valve piston, (2) addition of a brake model, and (3) providing for two hydraulic fluids in a system. The technique used to develop analytic models of the brake hydraulic system was verified using frequency response test data obtained during the previous program and reported in Reference 2.

The results of this study indicate that the two-fluid brake hydraulic system can have frequency response characteristics very nearly equal to the predicted "as-built" KC-135 characteristics through the first mode (the frequency where 90^{0} phase shift occurs) with the appropriate hardware configuration. The results also predict the second mode response although the predicted peak gain is greater than anticipated in the actual system. The reason for the large peak gain is that the HSFR analytic model is based on linear system characteristics. The major source of damping in the "as-built" system is the non-linear pressure drop at the deboost valve ports. These minor pressure losses vary as the square of the flow rate, but the HSFR program uses a pressure drop relation that is linearized about a typical flow chosen by the user.

During the course of the evaluation of various FHBS concepts (Task 1), Alternate 5 was identified as the tentative prime candidate system. In addition, system installation restraints were identified at the design coordination meeting held at BMAC Wichita on October 12, 1983. Therefore, a series of system design concepts for Alternate 5 were examined and compared to the performance objectives for the brake antiskid system. These studies lead to revising the line sizes and to incorporating a one-way restrictor in the MIL-H-5606 fluid portion of the system downstream of the shuttle valve. The purpose of the one-way restrictor is to add pressure drop, i.e., system damping, during the pressure application portion of the brake antiskid cycle to prevent brake pressure overshoot. Pressure overshoot can cause secondary wheel skids.

The frequency response was also determined for fluid temperatures of $-65^{o}F$ and $160^{o}F$ for the Alternate 5 and the "as-built" KC-135 systems. These data indicate the two-fluid brake system has better frequency response characteristics than the "as-built" KC-135 system at $-65^{o}F$. The two fluid system performance at $70^{o}F$ and $160^{o}F$ for the restricted flow case has a lower first mode frequency by 1.5 Hertz and a lower first mode peak gain by 1.0 db than the "as-built" system.

As discussed above, this study demonstrated the usefulness of the HSFR analytic models during system design to guide the sizing of components and plumbing.

A.2 Simulation Verification

A.2.1 Technical Approach

This study used a modified version of the USAF-developed HSFR computer program. The program modifications were developed during the previous fireproof brake system program and the details were reported in Reference 2.

In summary, the modifications to the HSFR program (References 9 and 10) included: (1) adding a component subroutine to model the fluid separation

piston in the KC-135 deboost valve, (2) modifying the accumulator subroutine to model the brake, (3) revising the fluid properties look-up logic to provide for two hydraulic fluids, and (4) modifying the output subroutines to retrieve and print out the phase data. The fluid property tables in the modified HSFR were updated during this effort by incorporating the latest specific gravity and kinematic viscosity data for the AO-2 CTFE fluid that was available from the Materials Laboratory (AFWAL/MLBT). Also, the coefficients and exponents for the equations used to adjust the tabulated properties of the CTFE fluid for pressure and temperature were revised based on the new data.

The frequency response data generated by the HSFR program were used to calculate the gain and phase shift relationship between the antiskid valve discharge pressure (input) and the pressure at each brake assembly (output). These data are presented in the Bode plot format. Gain data for each case shown has been normalized at 1.0 Hz.

The following five step procedure was developed to validate the HSFR simulations of the "as-built" KC-135 system and the FHBS systems:

Step 1. Reimplement the HSFR program on the Boeing Computer Services CDC-6600 system.

Step 2. Revise the HSFR source code to the two-fluid brake version, identified as HSFR2FB. Verify the accuracy of the revision by comparing the output data with the data generated during the previous contract.

Step 3. Develop a HSFR model of the single fluid KC-135 laboratory test system used in the previous contract. Verify the model with test data previously obtained from the test system. During this step, conduct sensitivity studies of hose compliance, deboost valve seal drag, and brake dynamic stiffness and effective mass to improve the correlation of analytic data to laboratory data.

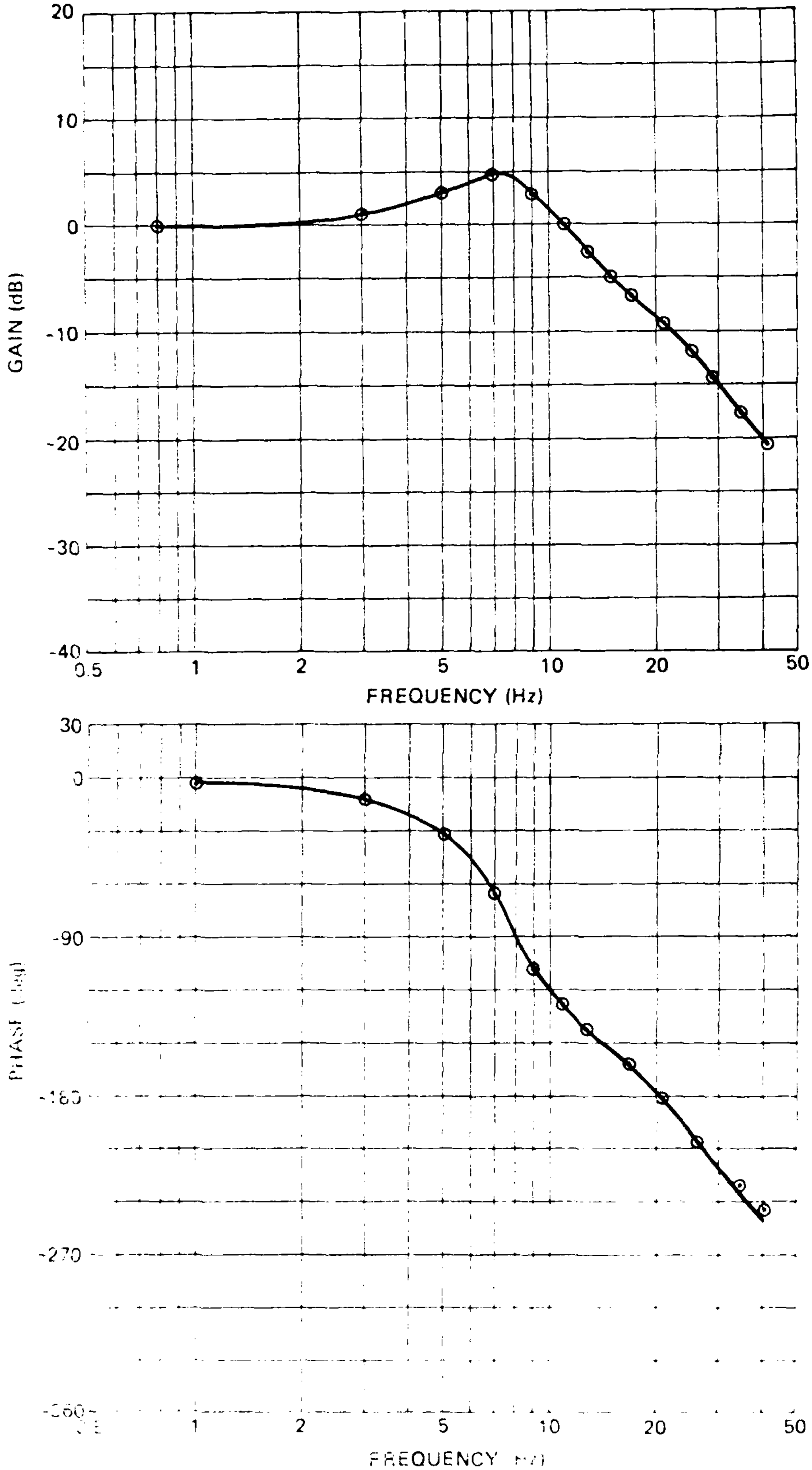
Step 4. Verify that a valid model of the two-fluid test system can be obtained by converting a verified one-fluid system model to a two-fluid configuration. Use the model developed in Step 3 and verify the resulting two-fluid system model with test data obtained during the previous program. Limit the conversion from the single fluid to two-fluid model to using the physical properties of the CTFE fluid, repositioning the deboost valve piston for the fluid separation function, and revising the gain for the HSFR subroutine VALVE, which is used to model lumped minor losses, to account for the density of the CTFE fluid.

Step 5. Prepare the simulation of the "as-built" KC-135 configuration and the candidate two-fluid systems using the techniques developed in Steps 3 and 4. Use the values of hose compliance, seal drag, and brake dynamic stiffness and effective mass developed as part of Step 3 for these models.

A.2.2 Verification Results

Figure A.1 shows the correlation of the HSFR2FB computer program results with the frequency response data calculated during the previous contract. The data defining the system configuration are shown in Table A.1 and were taken from Reference 2. These results verify that the modifications previously developed for the analysis of two-fluid brake hydraulic systems have been correctly implemented in HSFR2FB.

The math model schematic for the test system is shown on Figure A.2. The analytical results for the standard MIL-H-5606 fluid system model are compared with the test results on Figure A.3. Figure A.4 shows the correlation between the test data from the two-fluid test system and the output of the two-fluid model that was obtained by converting a single fluid model to a two-fluid model (Step 4). These figures show excellent correlation between the analytical data and the test results for the fundamental mode of the systems. The computer program models also predict the existence of the second mode though no special effort in modeling or test techniques were made to obtain this mode. The test results shown here are from the test data used to prepare Figure 19(a) and 20(a) of Reference 2; i.e., the test curves on Figures A.3



Notes:

1. $P_{brake}/P_{antiskid\ in}$.
2. Performance curve from reference 1., Appendix A, Figure 3.2
⊙ HSFR2FB output.

A

Figure A.1. Verification of Source Code HSFR2FB

Table A.1. HSFR Brake Hydraulic System Model Data for Source Code Verification[a]

Description	Item number	HSFR model	HSFR parameters
Pump	1	Empirical pump	Pump pressure = 200 lb/in^2
Antiskid valve	2	Valve	Valve gain = 25 lb/in^2/CIS
Antiskid valve to deboost valve	3	Line[b]	Line length = 27.0 in Outside diameter = 0.5 in Wall thickness = 0.049 in
Deboost valve	4	Line[b]	Line length = 1.62 in Outside diameter = 2.57 in Wall thickness = 0.22 in
		Piston	Area 1 = 3.533 in^2 Area 2 = 11.027 in^2 Mass = 0.002 lb-sec^2/in Damping = 0.2 lb-sec/in
		Volume	Volume = 10.58 in^3
		Line[b]	Line length = 0.4 in Outside diameter = 4.15 in Wall thickness = 0.19 in
Deboost valve to hose	5	Line[b]	Line length = 170.0 in Outside diameter = 0.5 in Wall thickness = 0.049 in
Hose	6	Hose[c]	Line length = 81.0 in Inside diameter = 0.5 in
Brake line	7	Line[b]	Line length = 63.0 in Outside diameter = 0.375 in Wall thickness = 0.035 in
Brake hose	8	Hose[c]	Line length = 24.0 in Inside diameter = 0.375 in
Brake	9		Effective mass = 3.944 lb-sec^2/in Piston radius = 1.95 in Wall thickness = 0.25 in
		Accumulator[b]	Legnth = 0.46 in Stiffness = 276,750 lb/in Damping = 1,483 lb-sec/in
[a]From reference 2, Appendix A Table 3.2 [b]Modulus of elasticity = 28,000,000 lb/in^2 [c]Bulk modulus = 16,000 lb/in^2			

A

• System configuration from the antiskid valve to the brake

Description	Line number	Line size[a]	Line length (in)
Antiskid valve to fuse	1	8S49	11
Fuse to shuttle	2	8S49	16
Deboost to hose	3	8S49	170
Hose	4	0.5 in	81
Brake line	5	6S35	63
Brake hose	6	0.375 in	24

[a] Line size tubing designation:

8 S 49

- 49 — Wall thickness (e.g., 0.049 (in))
- S — Stainless steel
- 8 — Outside diameter, in sixteenth (in)

Reference: from AFWAL-TR-2080.

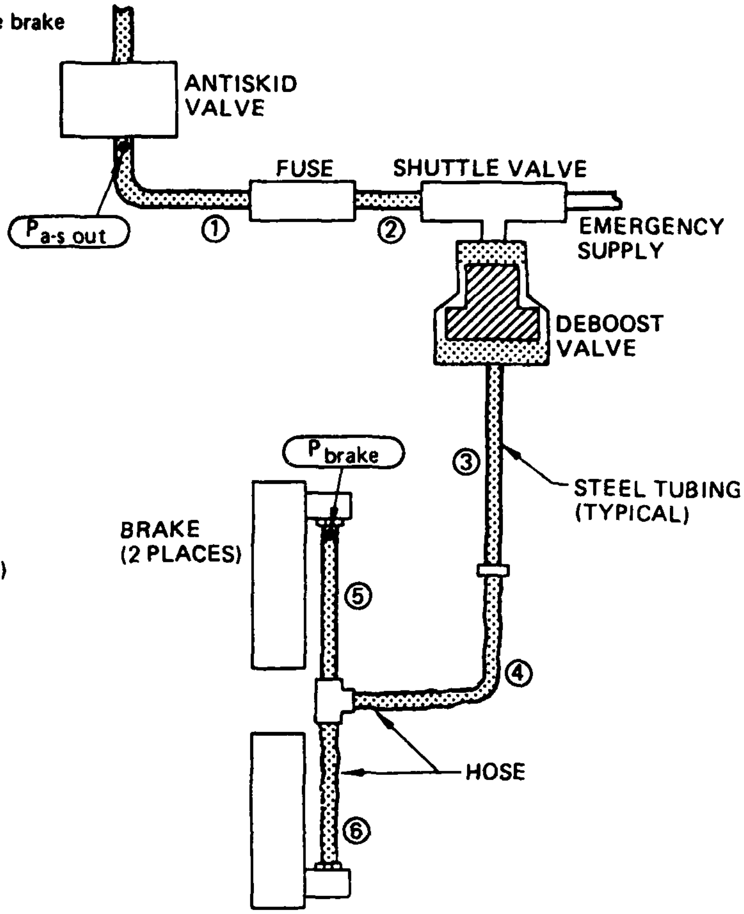
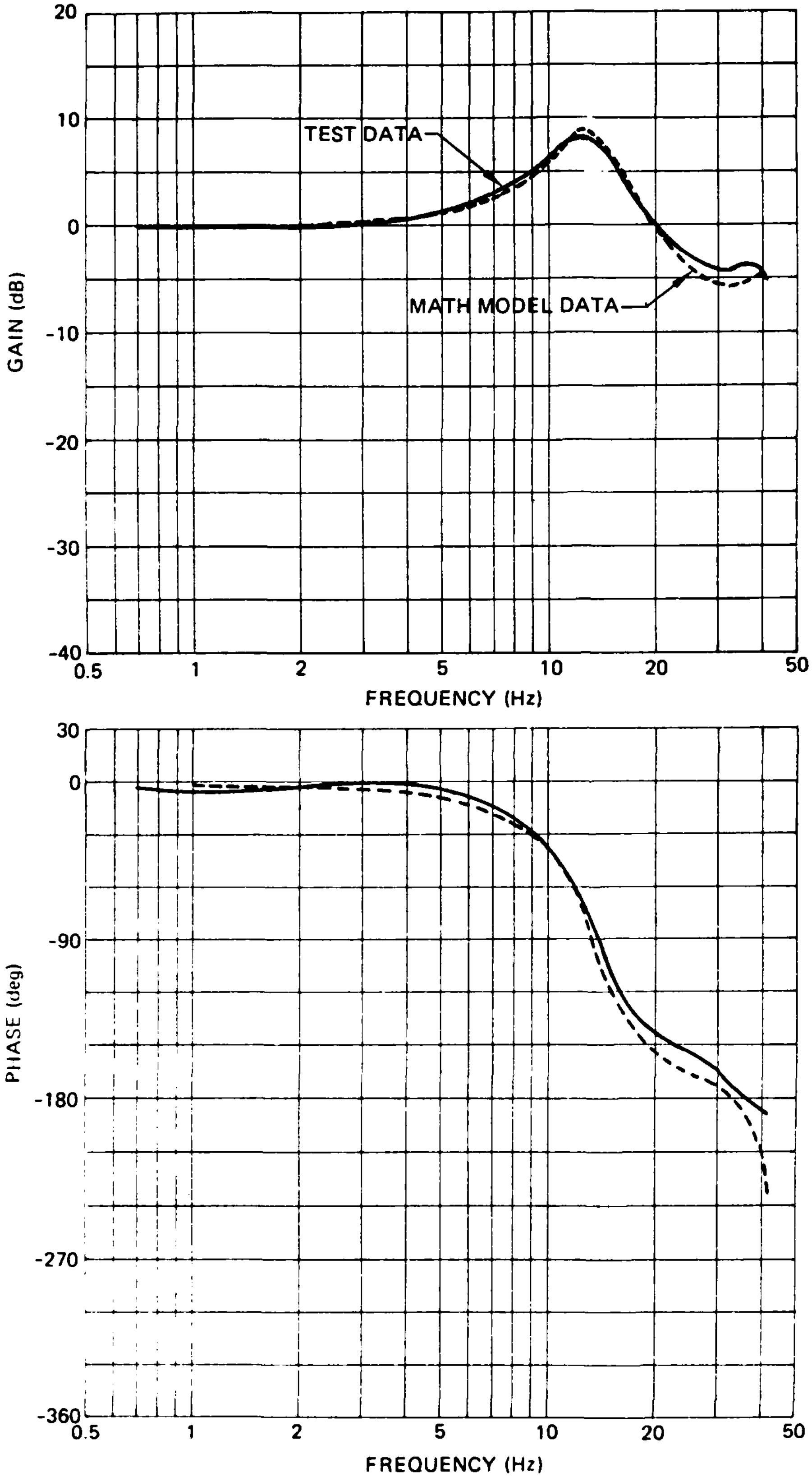


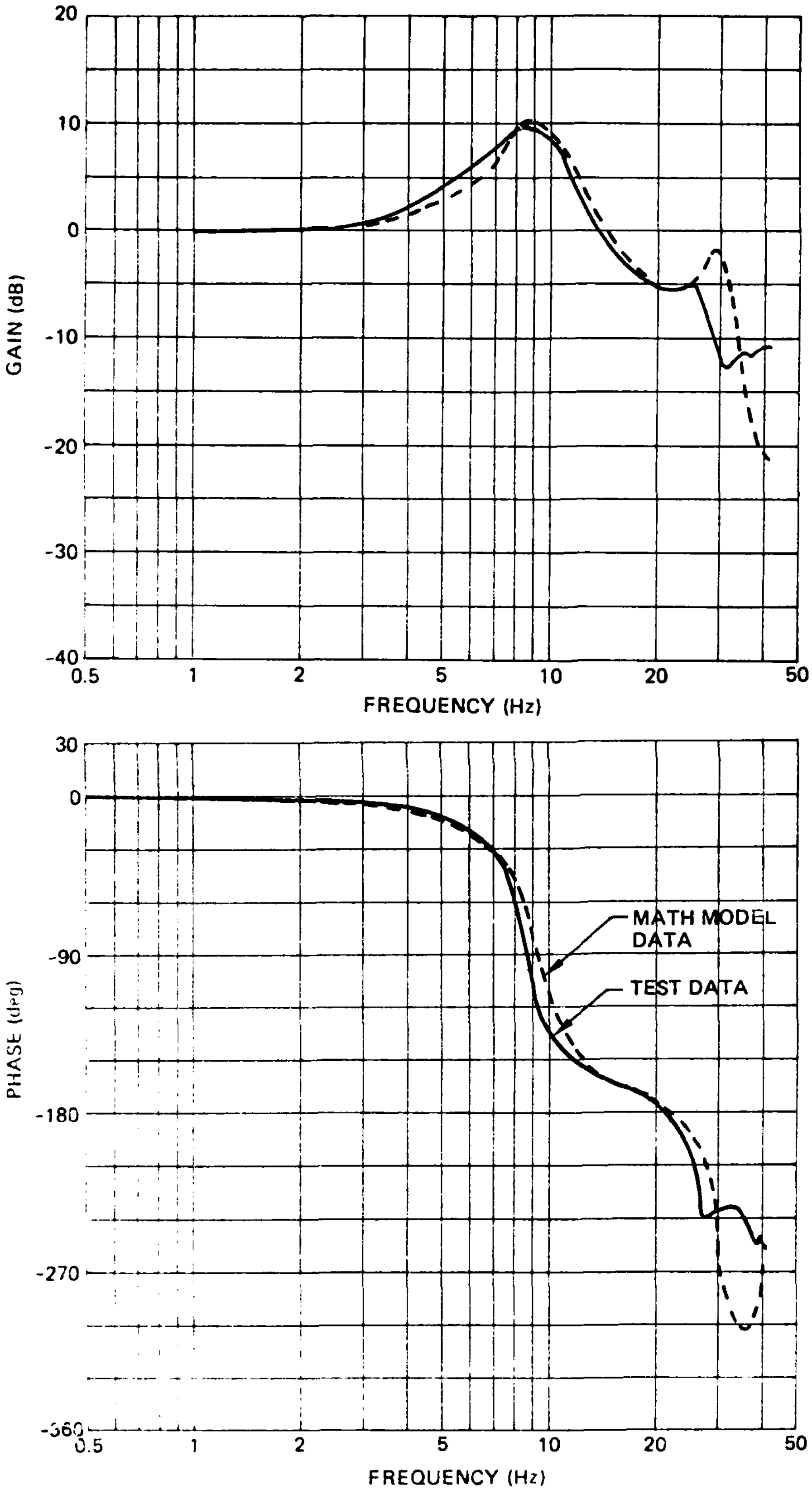
Figure A.2. KC-135 Brake Hydraulic System Laboratory Test Configuration



Notes:

1. $P_{brake}/P_{antiskid\ out}$.
2. Test data from reference 1.
3. Standard KC-135 Brake Laboratory Test System

Figure A.3. Data Correlation for Standard KC-135 Brake Laboratory Test System



Notes:

1. $P_{brake}/P_{antiskid\ out}$.
2. Test data from reference 1.
3. MIL-H-5606 and CTFE (AO-2) fluids.

Figure A.4. Data Correlation for Two-Fluid KC-135 Brake Laboratory Test System

and A.4 are the total system response, Figure 19(a), less the antiskid valve response, Figure 20(a), of the reference.

The model characteristics for hose diametrical stiffness, deboost valve damping (both seal drag and hydraulic minor losses), and brake dynamic stiffness and effective mass, developed in Step 3 and verified by Step 4, were used in the math model of the "as-built" KC-135 and the design studies of the two-fluid system concepts. The sensitivity study determined that system frequency response was most sensitive to the damping provided by the hydraulic minor losses, such as generated by the deboost valve discharge port, and the brake parameters. The hose compliance effects were observable (e.g., Figure 12 of Reference 2) and the seal drag contribution to system damping was negligible.

A.3 Discussion of Results

A.3.1 Stopping Performance Criteria

An objective of the fireproof hydraulic brake system design, as stated in paragraph 4.2 of the Statement of Work for this contract, is the selected two-fluid system design shall be capable of providing at least equivalent stopping distance performance as the "as-built" KC-135 aircraft brake system. The frequency response of the applicable system concepts was predicted to provide an assessment, during the Task 1 design phase, of the stopping performance of the candidate FHBS concepts.

The HSFR computer program used to do the frequency response analysis is a linear system analytical tool in the frequency domain. However, the overall system performance factor being examined, airplane stopping distance, is a non-linear phenomenon in the time domain. Though the brake antiskid does operate in a cyclic manner, it is not a linear system operating with sinusoidal signals.

However, the results of the frequency response analysis can provide a qualitative evaluation of stopping performance capability by the comparative analysis of the frequency response of a proposed design to that of a proven design. The factors that were examined in the comparative analysis were (1) the first mode breakpoint frequency, which is defined as the 90° phase shift frequency, (2) the phase shift at the predominant frequencies of antiskid cyclic activity, which are within the 3 to 5.5 Hertz range, and (3) the peak amplitude ratio of all modes occurring up to 40 Hertz. The system response outside the frequency range of antiskid valve activity is examined because commands to the antiskid valve include step and ramp signals; waveforms that include higher frequency signals. The existence of strong higher mode responses also indicate a lightly damped system that can allow significant pressure overshoot in response to a step command.

In conducting this comparative analysis, several factors must be considered. First, the known performance data (i.e., the frequency response data in Figures A.3 and A.4 and the stopping distance data listed in Table A.2) were obtained from the KC-135 lab test system during the previous program. No frequency response test data of the "as-built" KC-135 system are available for this program.

Second, the stopping distances (Table A.2.), shown for the Reference 2 two-fluid test system, were predicted with the assumption that all four antiskid wheel pair circuits were modified. For this program, only one antiskid wheel pair circuit is to be converted to a two-fluid system. Therefore, as a first approximation, it is assumed that the change in stopping distance shown for this configuration would be 25% of the difference in the values shown in Table A.2 for the change in frequency response shown between Figures A.3 (standard system) and A.4 (two-fluid system).

Third, the tolerance band on the frequency response data must be considered. The factors contributing to the tolerance band for the two-fluid system analysis results are the uncertainty in the CTFE fluid bulk modulus and the uncertainty in predicting pressure drop through "minor loss" factors due to

Table A.2. Effect of Two-Fluid Brake System on Stopping Performance

Test and description	Peak available runway friction	Stopping distance (ft) Ambient Standard system	Ambient Two-fluid system	-40°F Standard system	-40°F Two-fluid system	+160°F Standard system	+160°F Two-fluid system
Test 5—constant runway friction	0.6	1,879	1,935	1,895	2,066	1,825	1,901
	0.5	2,234	2,353	2,240	2,382	2,158	2,296
	0.4	2,694	3,120	2,779	2,837	2,650	3,197
	0.3	3,784	4,816	3,548	3,604	3,942	4,668
	0.2	7,214	8,508	5,452	5,422	6,706	7,520
	0.1	13,325	13,220	10,396	9,799	12,828	12,430
Test 6—wet runway	0.1 to 0.5	4,725	5,543	4,331	4,380	4,608	5,028
	0.1 to 0.35	5,963	7,098	5,208	5,255	5,936	6,453
Test 7—step friction	0.1 to 0.5	3,957	4,521	6,105	5,917	3,807	4,133
Note: Data from reference 2, Table 7							

oscillatory flow. At the direction of AFWAL/MLBT, the bulk modulus data for the AO-8 version of the CTFE fluid, determined during the initial fireproof hydraulic fluid contract and reported in Reference 11, were used for the AO-2 CTFE fluid. The "minor loss" factors were developed using steady state flow "K-loss" data presented in Reference 12. These data were used in the HSFR VALVE component subroutine in the form of a flow gain linearized about the peak flow rate at 6 Hertz.

An additional factor to be considered when evaluating stopping performance is the effect of tolerance stackup in hardware. As an example, Figure A.5 presents data, taken from Reference 2, showing the variation in brake system frequency response due to changing the antiskid valve. This data, obtained from three "in-spec" antiskid valves, shows that first mode peak gain varied by 1.2 db, the second-mode peak gain varied by 7 db, and the 90^{o} phase shift frequency varied by 1.2 Hertz.

A.3.2 Analysis of System Concepts

A frequency response analysis was accomplished for two configurations: the baseline FHBS system and Alternate 5. The other alternate designs were similar to the FHBS baseline system or Alternate 5 concept, and therefore were not included in the frequency response analysis.

The predicted frequency response of the "as-built" KC-135 configuration for both the standard MIL-H-5606 fluid system and the two-fluid system is shown by Figure A.6. These results indicate that changing the KC-135 to a two-fluid system without changing line sizes, and only revising the deboost valve to function as a fluid separator, would cause an unacceptable breakpoint frequency change from 13.4 Hz to 9.6 Hz. Therefore the "as-built" system was modified to increase the line sizes so that an acceptable breakpoint frequency would be obtained.

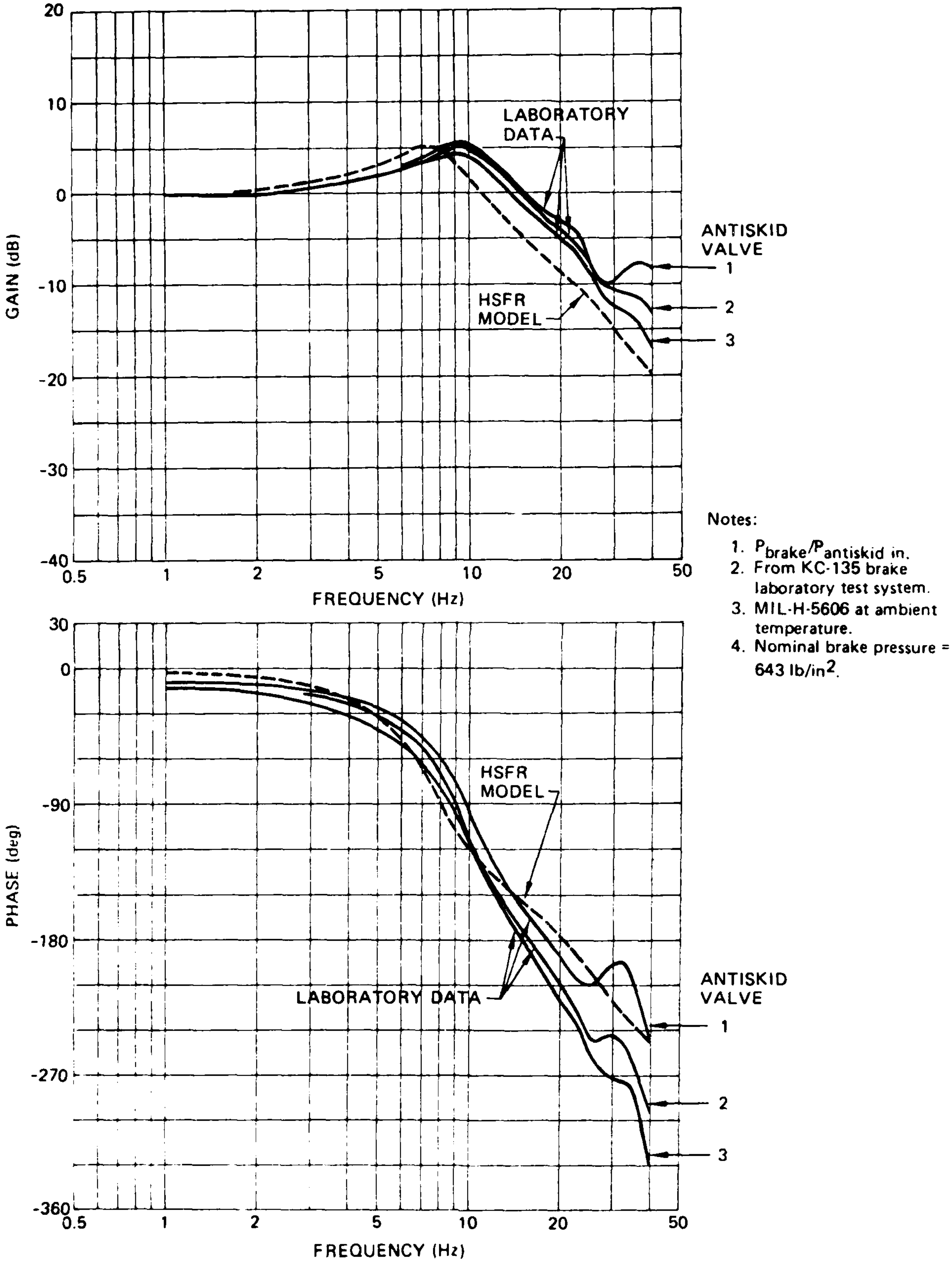
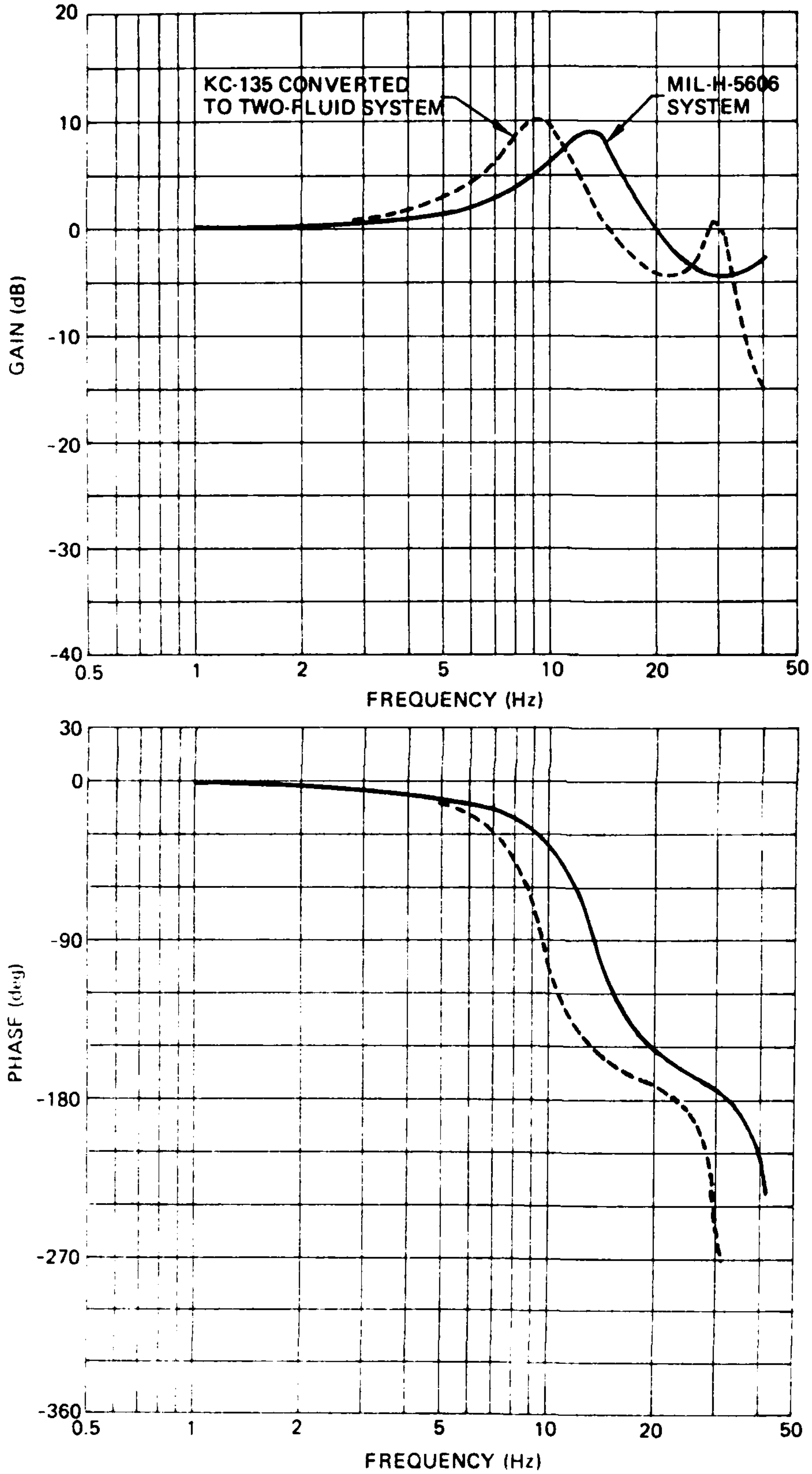


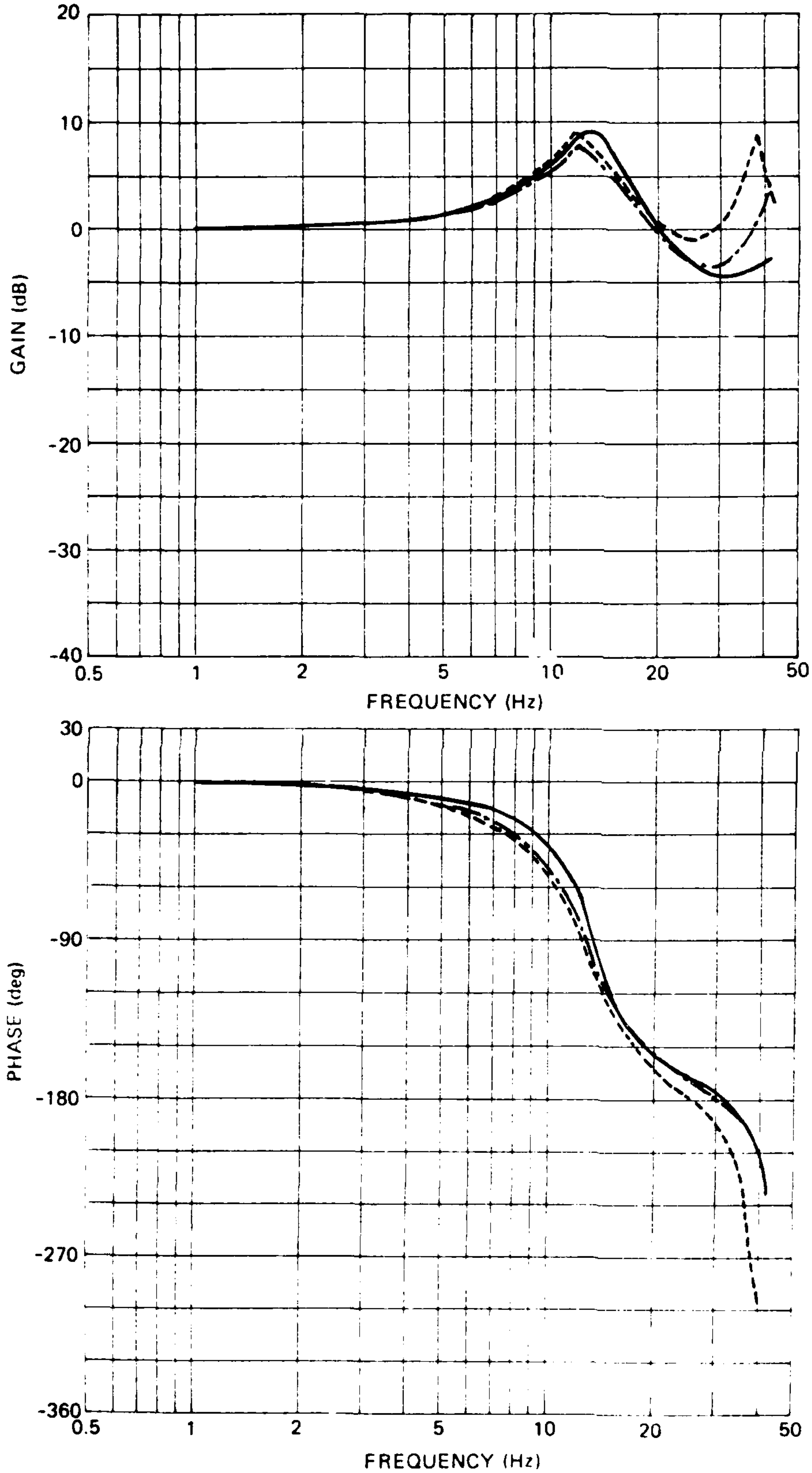
Figure A.5. Influence of Antiskid Valve Performance on Brake System Response



Notes:

1. $P_{brake}/P_{antiskid\ out}$.
2. Fluid temperature = 70°F.

Figure A.6. Predicted Response of As-Built KC-135 Brake Hydraulic System



Notes:

1. $P_{brake}/P_{antiskid\ out}$.
2. MIL-H-5606 and CTFE (AO-2) fluids.
3. Configuration data on figure A.8.

Legend:

- KC-135 MIL-H-5606 system
- Baseline two-fluid system
- Alternate 5

Figure A.7. Predicted Response of Candidate Two-Fluid Brake Hydraulic Systems

Figure A.7 shows the frequency response of the baseline two-fluid system and Alternate 5. For ease of comparison, the predicted "as-built" KC-135 performance is included in Figure A.7. These data show that models for both two-fluid designs predict a break point of 12.6 Hz. Also, the phase shift for the two fluid systems is only 2^{o} more than the "as-built" system at the main antiskid frequencies of 3 to 5.5 Hertz.

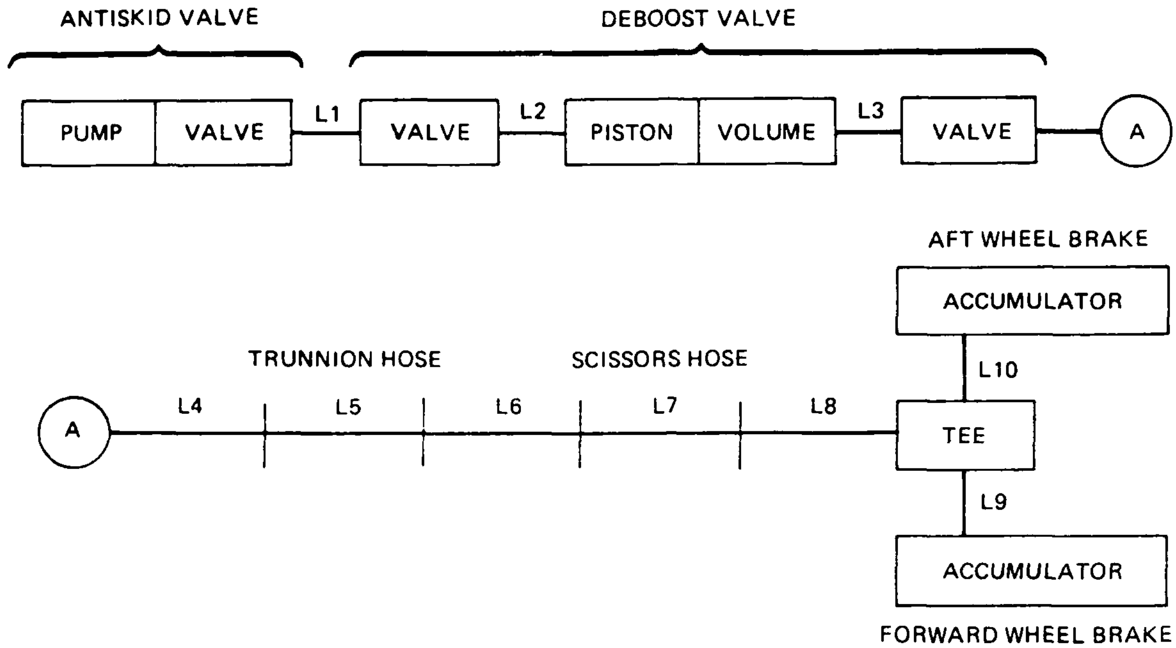
These analyses were based on the assumption that the major components of the brake system, e.g., shuttle valve, deboost valve and, for Alternate 5, the reservoir/separator, would be located at approximately the same location as the deboost and shuttle valves on the "as-built" KC-135. The configuration data for the KC-135 and baseline FHBS models are summarized on Figure A.8 and for the Alternate 5 design on Figure A.9.

A.3.3 Design Development of Primary Candidate System

During the course of the evaluation of the various FHBS concepts (Task 1), Alternate 5 was identified as the tentative prime candidate system. As part of this project a design coordination meeting was held at the BMAC Wichita. One result of the meeting was a new installation location for the reservoir/separator and deboost valve for Alternate 5. The location identified increased the length of the hydraulic lines. Therefore, additional frequency response analyses of Alternate 5 were done to evaluate the impact of installation restrictions on brake system response.

The impact of relocating the components is shown by the response curves identified as "5A" on Figure A.10. The breakpoint frequency is reduced by 1.4 hertz and the phase shift at 5 Hertz is increased by 4^{o} compared to Alternate 5.

To increase the breakpoint frequency, the system inheritence (a function of fluid density to flow area) was reduced by increasing the diameter of selected lines. Because of installation problems in the landing gear strut and truck areas, not all of the increased diameter lines could be in the CTFE fluid portion of the system. Therefore, the diameter of one line upstream of the



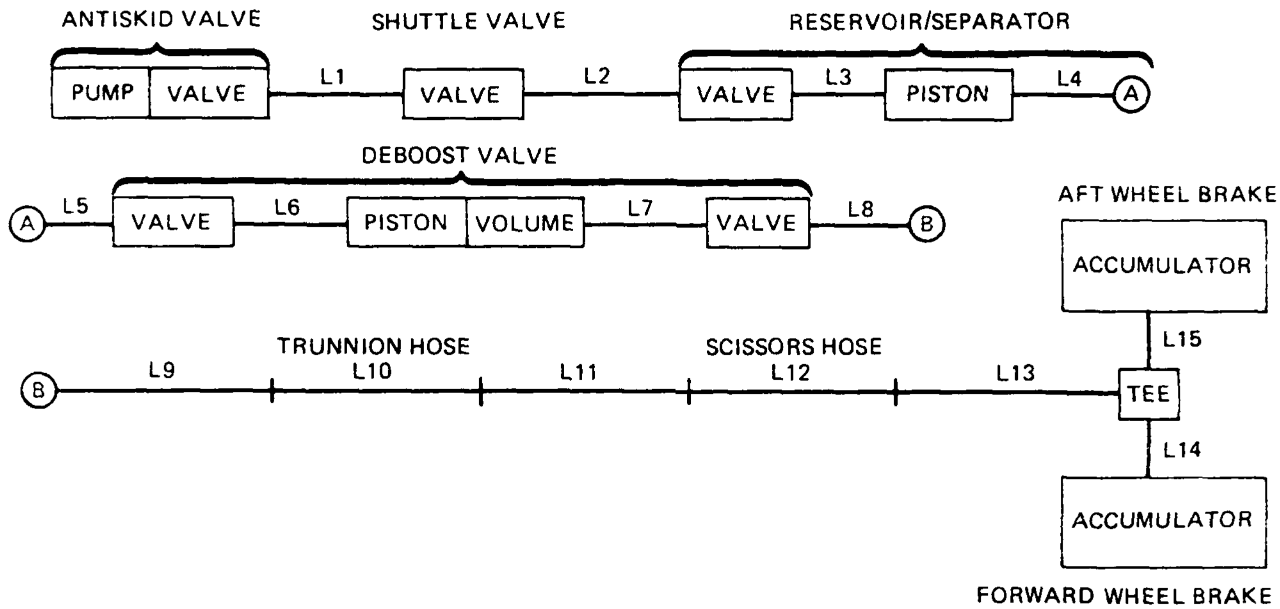
Line No. \ System	As-built KC-135	Baseline FHBS
L1	8S49-27	8S49-27
L2	Length 0.6 in Inside diameter 2.12 in	Length 1.60 in Inside diameter 2.12 in
L3	Length 1.35 in Inside diameter 3.75 in	Length 0.35 in Inside diameter 3.75 in
L4	8S49-112	12S65-112
L5	8MP406-29	12MP625-29
L6	8S49-50	12S65-50
L7	8MP406-52	12MP625-52
L8	8S49-18	12S65-18
L9	6S35-63	10S58-63
L10	6MP312-23	8MP406-23

NOMENCLATURE:

X Y Z — L

- L: Length (in)
- Z: Inside diameter for hose; wall thickness for tube, in thousandths (in)
- Y: Material: S = STL steel
  MP = Medium pressure hose (MS28741)
- X: Line size, in sixteenths (in)

Figure A.8. Configuration Data for KC-135 and Baseline System HSFR Models



System Tube and Hose Data

Line No. \ System No.	5	5A	5B	5C	5D
1	8S49-21 ▷1	8S49-27	8S49-25	▷2	▷3
2	Not used	8S49-72	10S58-72		
5	8S49-6	6S39-1.2	6S39-1.2		
8	12S65-112	12S65-148	16S68-60		
9	Not used	Not used	12S65-88		
10	10MP500-29	10MP500-29	10MP500-29		
11	12S65-50	12S65-50	12S65-50		
12	12MP625-52	12MP625-52	12MP625-52		
13	12S65-18	12S65-18	12S65-18		
14	8S49-63	8S49-63	8S49-63		
15	8MP406-23	8MP406-23	8MP406-23	▷2	▷3

▷1 Nomenclature:

X Y Z L

- L — Length (in)
- Z — Inside diameter for hose; wall thickness for tube, in thousandths (in)
- Y — Material: S = STL steel; MP = Medium pressure hose (MS28741)
- X — Line size, in sixteenths (in)

▷2 Alternate 5C, same as 5B except one-way restrictor added at deboost valve exit (between lines L7 and L8).

▷3 Alternate 5D, same as 5B except one way restrictor added at reservoir/separator inlet.

Figure A.9. Configuration Data for Alternate System 5 Design Study

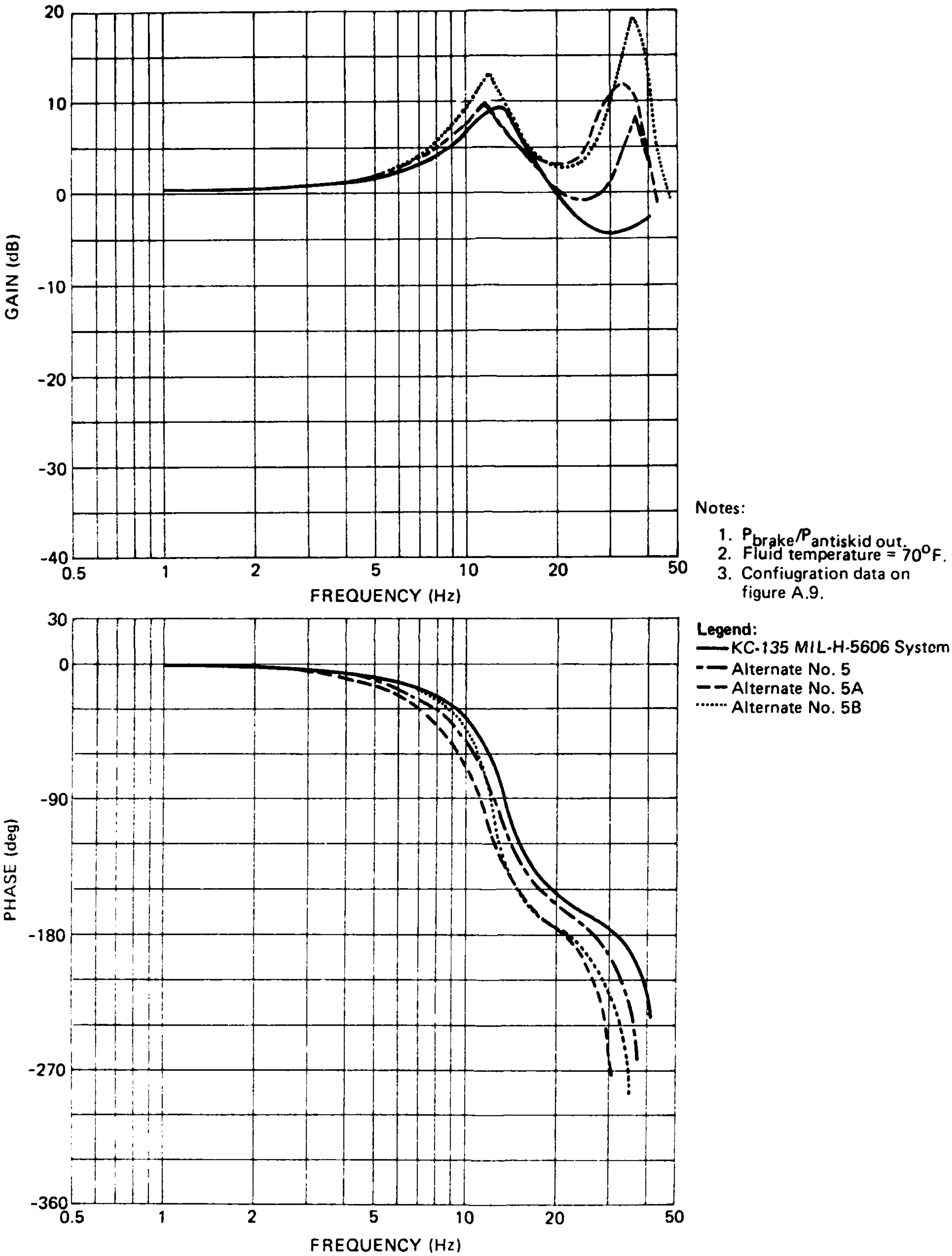


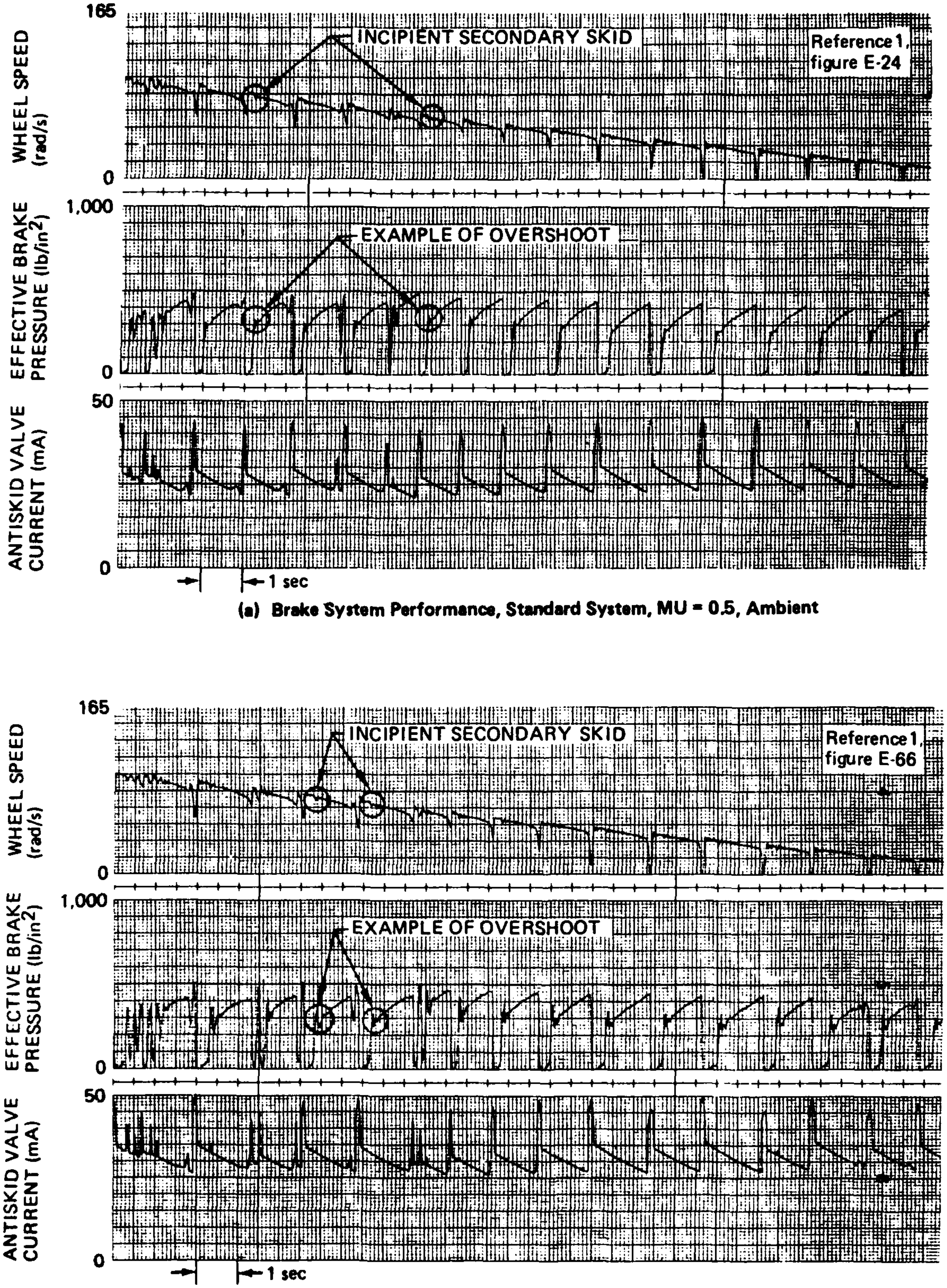
Figure A.10. Frequency Response of Alternate Design Variations

reservoir/separator was increased to reduce system inheritence. Increasing line diameter also lowers system damping and thereby reduces the phase shift in the frequency range of the antiskid valve activity.

The response data identified as "5B" on Figure A.10 is for a system like "5A" except for increased diameter lines between the shuttle valve and the reservoir/separator inlet, and between the deboost valve exit and the tee at the outboard wall of the wheelwell. Line lengths and diameters for each configuration are tabulated on Figure A.9. These data indicate that for system "5B", compared to system "5", the breakpoint frequency is only 0.4 Hertz lower and the phase shift at 5 Hertz is not as great and, at -11°, is the same value as for the "as-built" KC-135 system. Therefore, from the viewpoint of phase shift (time lag), "5B" is adequate. Examining the gain data shown on Figure A.10, the first mode peak gain of "5B" is 3.5 db greater than for the "as-built" KC-135 system. In addition, the math model predicts for "5B" a very strong second mode response at 37 Hertz with a 17.6 db peak amplitude ratio.

The object now is to relate the significance of these frequency response data to the time domain operation of the antiskid system. The large peak amplitude of "5B" indicates a system with less damping than the "as-built" KC-135 system. A lightly damped mass-spring system has significant overshoot in response to a step command. The antiskid system commands a step increase in brake pressure immediately after the wheel recovers from a skid. Reduced system damping would result in a larger than required (commanded) hydraulic pressure on the brake. The overshoot pressure may cause a secondary skid, thereby reducing stopping performance. To determine how sensitive the "as-built" KC-135 system may be to peak amplitude ratio, the frequency response and antiskid system performance data for the KC-135 lab test system, obtained during the previous program, Reference 2, were examined.

Figures A.3 and A.4 present the frequency response data recorded from the standard and two-fluid configurations of the KC-135 brake lab test system. The peak amplitude ratio for the "as-built" system (Figure A.3) is 8.2 db and



(a) Brake System Performance, Standard System, MU = 0.5, Ambient

(b) Brake System Performance, Two-Fluid System, MU = 0.5, Ambient

Figure A.11. Predicted Brake Antiskid Performance From KC-135 Laboratory Test System

for the two-fluid system (Figure A.4) it is 9.7 db; an increase of 1.5 db. Figure A.11 presents antiskid performance measured on the test system for both of these configurations and reported in the cited reference. These data show that the brake pressure overshoot for the two-fluid system is substantially larger than for the "as-built" system. As pointed out on Figure A.11, the larger overshoot of the lower damped two-fluid system leads to the development of secondary skids. Therefore it was concluded that the KC-135 brake antiskid system is sensitive to pressure overshoot and that the predicted 3.5 db increase between the "as-built" KC-135 and "5B", Figure A.10, would degrade stopping performance.

In summary, two performance objectives of an antiskid system are that the pressure decay time following an antiskid pressure dump command should be minimized (small phase shift) and that the brake pressure build up rate should follow the antiskid pressure application command and not overshoot or ring (controlled peak amplitude ratio). A one-way restrictor installed for free flow during pressure dump and restricted flow during pressure application can assist in meeting the two design objectives stated above. Therefore a design study, using the frequency response model, of one-way restrictor sizes and locations was undertaken. One-way restrictors are currently used in the E-4B, 757 and 767 brake systems.

Figures A.12 and A.13 summarize the final results of the one-way restrictor trade study by comparing the frequency response data for a one-way restrictor, located in either the MIL-H-5606 fluid portion or in the CTFE portion of the system, with the "as-built" KC-135 system. As shown on Figure A.12, when the one-way restrictor is located in the CTFE system (Configuration "5C") the reduction in peak gain for the second mode was approximately 1 db out of 18 db. The data in Figure A.13 show that when the one-way restrictor is located in the MIL-H-5606 fluid portion of the "5D" system, the peak gain for both the fundamental and second modes is significantly lower in the restricted flow case than for the free flow case. These results indicate that for with the one-way restrictor in the MIL-H-5606 fluid system, the potential for secondary skids is significantly reduced. Therefore, the remaining HSFR analyses was conducted using system "5D". The performance of the "5D" two-fluid system and

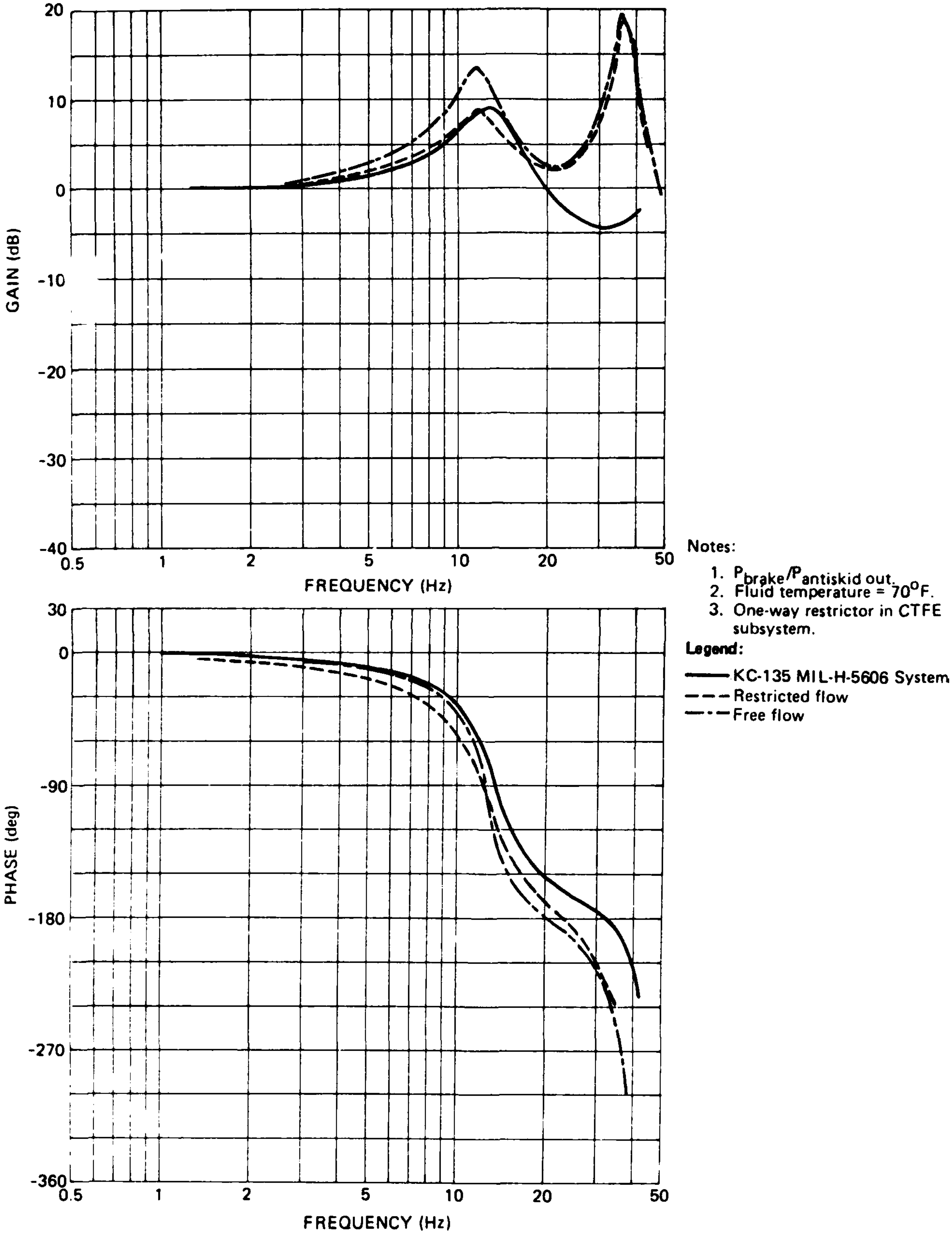
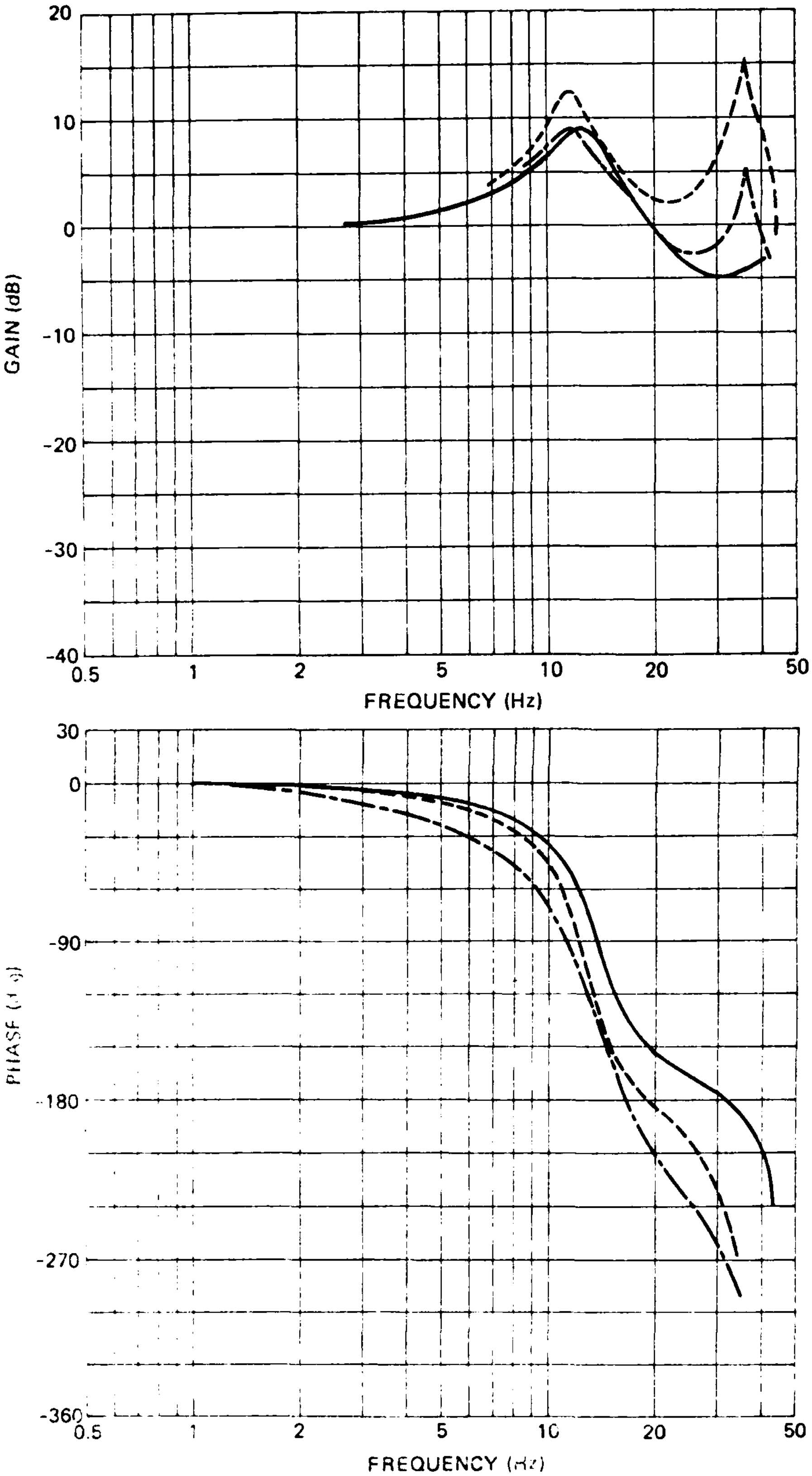


Figure A.12. Frequency Response of Design 5C (With One-Way Restrictor)



Notes:

1. $P_{brake}/P_{antiskid}$ out.
2. Fluid temperature = 70°F.
3. One-way restrictor in MIL-H-5606 subsystem.

Legend:

—— KC-135 MIL-H-5606 System
- - - - Free flow
—·—· Restricted flow

Figure A.13. Frequency Response of Design 5D (With One-Way Restrictor)

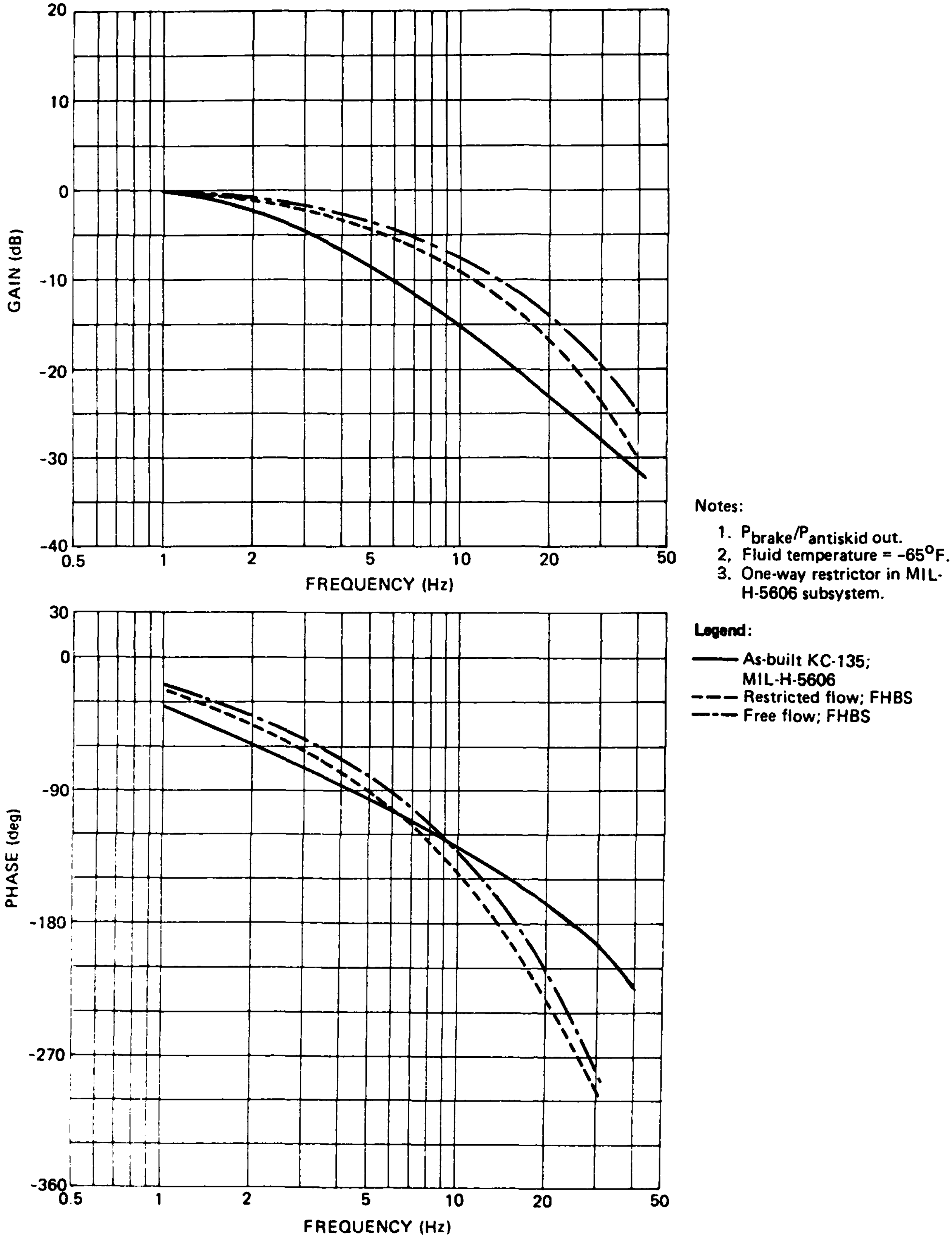


Figure A.14. Low-Temperature Frequency Response of Design 5D (With One-Way Restrictor)

the "as-built" KC-135 system was predicted using hydraulic fluid at -65°F and 160°F. The low fluid temperature data are shown on Figure A.14 and the high temperature data on Figure A.15.

The predicted response at -65°F, Figure A.14, shows that the break frequency for both the restricted flow and free flow cases is greater than predicted for the "as-built" KC-135 system. Though the gain for the two-fluid system is larger than for the KC-135 system for both the restricted-flow and free-flow cases, pressure overshoot is not a problem since the gain is never positive.

The high temperature response data, Figure A.15, shows similar response change between the two-fluid system and the "as-built" KC-135 system as were predicted using 70°F fluid (Figure A.13); compared to the "as-built" KC-135 system, the two-fluid system break frequency is reduced by 1.5 Hertz, the first mode peak gain for the restricted flow case is lower by 1 db, and for the free-flow case the first mode peak gain is 3 db greater.

A.4 Conclusions and Recommendations from Task 2

The frequency response analysis of the applicable two-fluid brake hydraulic system design variations developed in Task 1 has been completed. The frequency response math models were used to refine the system design to obtain brake system performance comparable to the predicted performance of the "as-built" KC-135 brake hydraulic system. A comparative analysis of the frequency response of the final two-fluid system design to the "as-built" KC-135 system for fluid temperatures of -65°F and 160°F was accomplished.

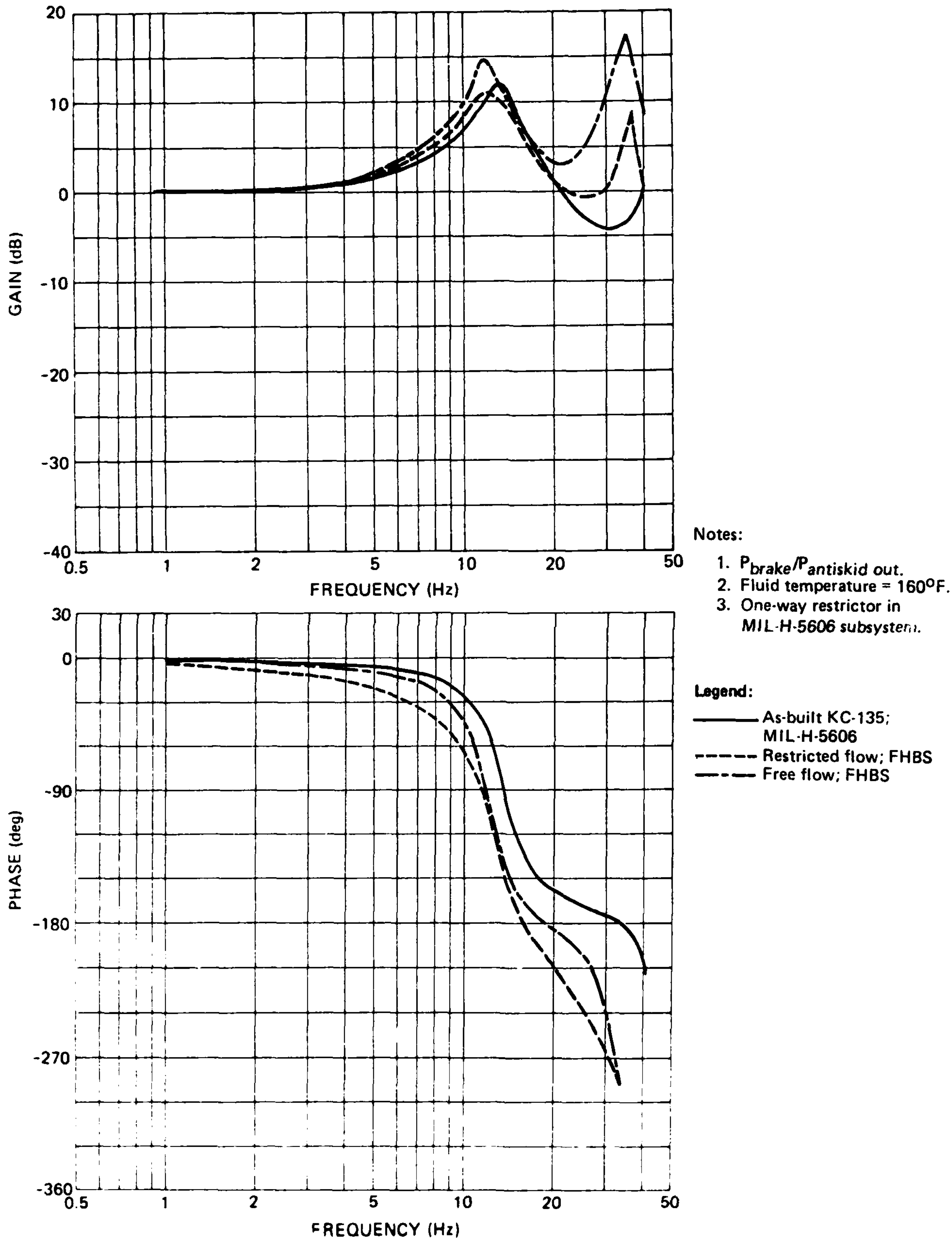


Figure A.15. High-Temperature Frequency Response of Design 5D (With One-Way Restrictor)

This analysis concluded that the two-fluid system performance at the extreme temperatures exceeded or equaled the relative performance of the two systems using 70°F fluid. Based on the frequency response analysis, it is recommended that system "5D", which incorporates a one-way restrictor in the MIL-H-5606 fluid portion of the system downstream of the shuttle valve, be the prime candidate design. Based on the design studies, it is recommended that the one-way restrictor have the following characteristics:

Rated flow rate: 10.36 gpm, MIL-H-5606 at 70°F
Free flow pressure drop: 45.0 psi maximum
Restricted flow pressure drop: 320 psi

APPENDIX B

COMPONENT FLIGHTWORTHINESS TEST PLAN

This appendix contains, in total, the planning document for the component flightworthiness testing, Revision A, dated June 28, 1984.

The page, figure, and table numbers have been changed from those in the document previously delivered to the USAF to be compatible with the format of this report.

TASK 5-FHBS COMPONENT TEST PLAN

The Fireproof Hydraulic Brake System (FHBS) shown in Figure B.1, is composed primarily of flight qualified, off-the-shelf hardware, in which the nitrile elastomeric O-ring seals have been replaced with modified Phosphonitrilic Fluoroelastomer (PNF) seals. The PNF seals have been evaluated by the AFWAL Material Laboratory and specified as the best elastomer available for the AO-2/CTFE nonflammable hydraulic fluid. These components are flightworthiness qualified on the basis of their previous formal qualification, and the minimal changes made to them. Components qualified by similarity are:

180-59838-1	Deboost Valve (Boeing P/N 5-85659-3) modified
180-59843-1	Fill and Bleed Valve (MS28889-2) modified
180-59844-1	Relief Valve (Vinson P/N A50081AB61) modified
180-59845-1	Brake Assembly (Bendix P/N 2600380-2) modified
180-59839-1	Restrictor Check-Valve (Crissair P/N 2C5310) modified
MS8005-	Hoses

The above components shall be disassembled and thoroughly cleaned per the following:

CLEANING PROCEDURE

The following cleaning procedure is recommended for hydraulic components, tubing and test stands being prepared for use with CTFE hydraulic fluid.

1. Clean with Stoddard Solvent per Federal Specification P-D 680.
2. Blow dry and evacuation dry.
3. Rinse with CTFE fluid.

After cleaning and modification of these components by installation of the PNF O-ring seals, a typical acceptance test consisting of a proof pressure and leakage test shall be performed. In addition the 180-59844-1 Relief Valve will be checked for cracking pressure.

New design components not previously qualified for aircraft use are the following:

180-59837-1	Reservoir/Separator Assy.
180-59840-1	Adapter/Restrictor Check Valve
180-59841-1	Tee-Deboost/Fill Valve

These components will be cleaned per the above procedure prior to assembly.

The adapter and tee (180-59840-1 and 180-59841-1) are static hydraulic fittings which will be qualified by a proof pressure test and materials inspection. The proof pressure test shall constitute a minimum of five

minutes at 6000 psi hydraulic pressure. Any discernible distortion, crack or leakage shall be recorded. All parts shall be checked against the detail drawing following the test. Damaged parts, distortion or leakage shall be cause for rejection.

The materials inspection shall determine the suitability of the part's base metal and/or protective finish for installation in a wheelwell environment.

The 180-59837-1 Reservoir/Separator Assembly shall be flightworthiness tested through the following series of tests (corresponding to the applicable requirements of MIL-H-8775 as shown in Table B.1):

1. Examination of product - Each reservoir/separator assembly shall be carefully examined to determine conformance to the requirements of MIL-H-8775 for design, weight, workmanship, marking, conformance to applicable AN or MS standard, and applicable Boeing drawings, and for any visible defects.

2. Proof Pressure and Static Leakage Test. Each Reservoir/Separator Assembly shall be tested with the rod horizontal with a MIL-H-5606 fluid supply bench connected to the 180-59839-1 Restrictor Check Valve. The MIL-H-5606 fluid side of the reservoir/separator shall be filled with fluid and bled of air to the greatest extent possible. The hydraulic pressure shall be slowly raised to 4500 psi minimum and held for five minutes. During and following the test, the assembly shall be visually inspected for distortion and leakage from the rod seal and from the drain holes on the side of the reservoir/separator barrel. Leakage in excess of two drops at either location shall be cause for rejection. Any discernible distortion shall be recorded. All parts shall be checked against their detail drawing following the test. Damaged or distorted parts, or leakage from static seals are cause for rejection.

Position the Reservoir/Separator vertically and pressurize to 3000 $\pm$ 300 psi for 4 hours, then reduce the pressure to 5$\pm$2 psi and maintain for 4 hours. Record any leakage from the CTFE port or at the rod/piston interface. Any leakage is cause for rejection.

The CTFE/AO-2 side of each reservoir/separator piston shall be subjected to proof pressure and leakage tests using CTFE/AO-2 fluid. Ascertain the bleed valve at the end of the rod is closed and capped. Connect the reservoir/separator to the CTFE/AO-2 supply cart and bleed to the greatest extent possible all air from the fluid. The hydraulic pressure shall be slowly raised to 4500 psi minimum and held for five minutes. During and following the test, the unit shall be visually inspected for distortion and leakage from the drain holes on the side of the reservoir/separator. Leakage in excess of two drops shall be cause for rejection. Any discernible distortion shall be recorded. All parts shall be checked against their detail drawing following the test. Damaged or distorted parts, or leakage from static seals are cause for rejection. Remove the CTFE/AO-2 supply cart plumbing and cover the ports of the reservoir/separator with leakproof caps.

3. Low Temperature Test. Component operational low temperature testing shall be conducted as part of the FHB System tests. Operational system tests shall be conducted after the system has been subjected to an ambient temperature of -65F for no less than eight hours. The operational tests shall consist of frequency and step response, and stopping performance. External leakage shall be checked for, and recorded at intervals.

External leakage through static seals other than a slight wetting external seal leakage shall not exceed one drop per ten cycles of endurance cycling.

(Note: Results from the earlier Fireproof Brake Hydraulic System program indicated that excessive leakage around PNF seals occurred during the -65F tests. This necessitated raising the test temperature to -40F where the leakage stopped.) In the event of excessive leakage during the proposed low temperature tests, the temperature will be raised to a temperature level where leakage no longer occurs and the testing continued.

4. Intermediate Temperature Tests. Intermediate temperature component operational testing per MIL-H-8775D, paragraph 4.5.6.2, shall be conducted as part of the FHB System tests. The operational tests shall consist of a frequency response scan at -30F, 0F, 30F, 60F, 90F, and 125F.

5. High Temperature Test. High temperature component operational testing shall be conducted as part of the FHB System tests. The system shall be maintained at 160F minimum while conducting frequency and step response, and stopping performance tests.

6. Endurance Test. Component endurance tests shall be conducted per the requirements of MIL-H-8775D, paragraphs 4.5.8.1 and 4.5.8.2, and Table B.1 (herein). At the completion of cycling, the components shall be disassembled and inspected for wear and/or damage.

7. Impulse Test. An impulse test of 100,000 cycles to 4500 psi shall be conducted per SAE ARP 1383 with reservoir/separator near mid-stroke.

8. Vibration Test. Vibration tests shall be conducted on the reservoir/separator in accordance with D-16046 "Vibration Test Requirements for Items of Equipment Installed in Model KC-135 Airplanes". The reservoir/separator CTFE side shall be filled to 50 percent and the port plugged. The MIL-H-5606 side shall be filled and bled, then pressurized to 15+5 psi for the duration of the vibration test. Any breakage of parts or total leakage of move than one drop per hour shall be cause for rejection.

9. Icing Test. Ice testing shall be conducted during the subfreezing portions of the intermediate temperature tests of paragraph 4 above. At -65F, -30F, 0F and 30F water shall be sprayed on the reservoir/separator following the test. Any sticking of the piston and/or damage to the rod scraper or seals shall be cause for rejection.

TABLE B.1 - MIL-H-8775D QUALIFICATION TEST REQUIREMENTS FOR FHBS

PARA. NO.	PARA. TITLE	COMMENTS	TEST PLAN PARA. NO.
4.5.1	Examination of product	Yes	1
4.5.2	Immersion	No 1	
4.5.3	Pressure tests	----------	
4.5.3.1	Proof pressure	Yes	2
4.5.3.2	Burst pressure	No 2	
4.5.4	Leakage tests	----------	
4.5.4.1	External leakage	Yes	2
4.5.4.2	Internal leakage	----------	
4.5.4.2.1	Qualification or first article tests	Yes	2
4.5.4.2.2	Quality conformance tests	Yes	2
4.5.5	Pressure drop	Not applicable	
4.5.6	Extreme temperature functioning tests	-------------	
4.5.6.1	Low temperature	Yes	3
4.5.6.2	Intermediate temperature	Yes	4
4.5.6.3	High temperature	Yes	5
4.5.6.4	Temperature limits	Not applicable	
4.5.7	Temperature rise	Not applicable	
4.5.8	Endurance	--------------	
4.5.8.1	General	Yes	6
4.5.8.2	Aircraft applications	Yes 3	6
4.5.8.3	Missile applications	Not applicable	
4.5.8.4	Impulse	--------------	
4.5.8.4.1	Actuators, pressure containers, etc.	Yes 4	7
4.5.8.4.2	Hose assemblies, etc.	No	

TABLE B.1 - MIL-H-8775D QUALIFICATION TEST REQUIREMENTS FOR FHBS (Cont.)

PARA. NO.	PARA. TITLE	COMMENTS	TEST PLAN PARA. NO.
4.5.9	Vibration	Yes	8
4.5.10	Humidity	No 1	
4.5.11	Fungus	No 1	
4.5.12	Sand and dust	No 1	
4.5.13	Salt fog	No 1	
4.5.14	Icing	Yes	9
4.5.15	Explosion proof	Not applicable	
4.5.16	Radio interference	Not applicable	
4.5.17	Actuation above system pressure	No 5	
4.5.18	Reliability	No 6	
4.5.19	Dielectric strength	Not applicable	

1 The design materials and protective finishes were selected to be unaffected by the fluids, humidity, fungus, sand and dust, and salt fog.

2 Will not be tested because of destructive nature of test. A detail stress analysis was submitted as part of the DI-E-3115B/M Mod. Documentation (Boeing D500-10401-1).

3 Endurance cycling per MIL-W-5013H shall consist of (1) 100,000 cycles of application and release of normal operating hydraulic pressure of 1500 psi and (2) 5000 cycles of application and release of maximum operating hydraulic pressure of 3000 psi. The endurance cycling shall be conducted as part of the system testing.

4 Impulse testing was not required for the original KC-135 component design, however 100,000 cycles of 4500 psi impulse cycles will be applied to the Reservoir/Separator.

5 Overpressure testing shall be waived on the basis that thermal overpressures cannot exceed the proof pressure due to the 1200 psi relief valve in the circuit.

6 Reliability testing is waived since this is a R&D test program.

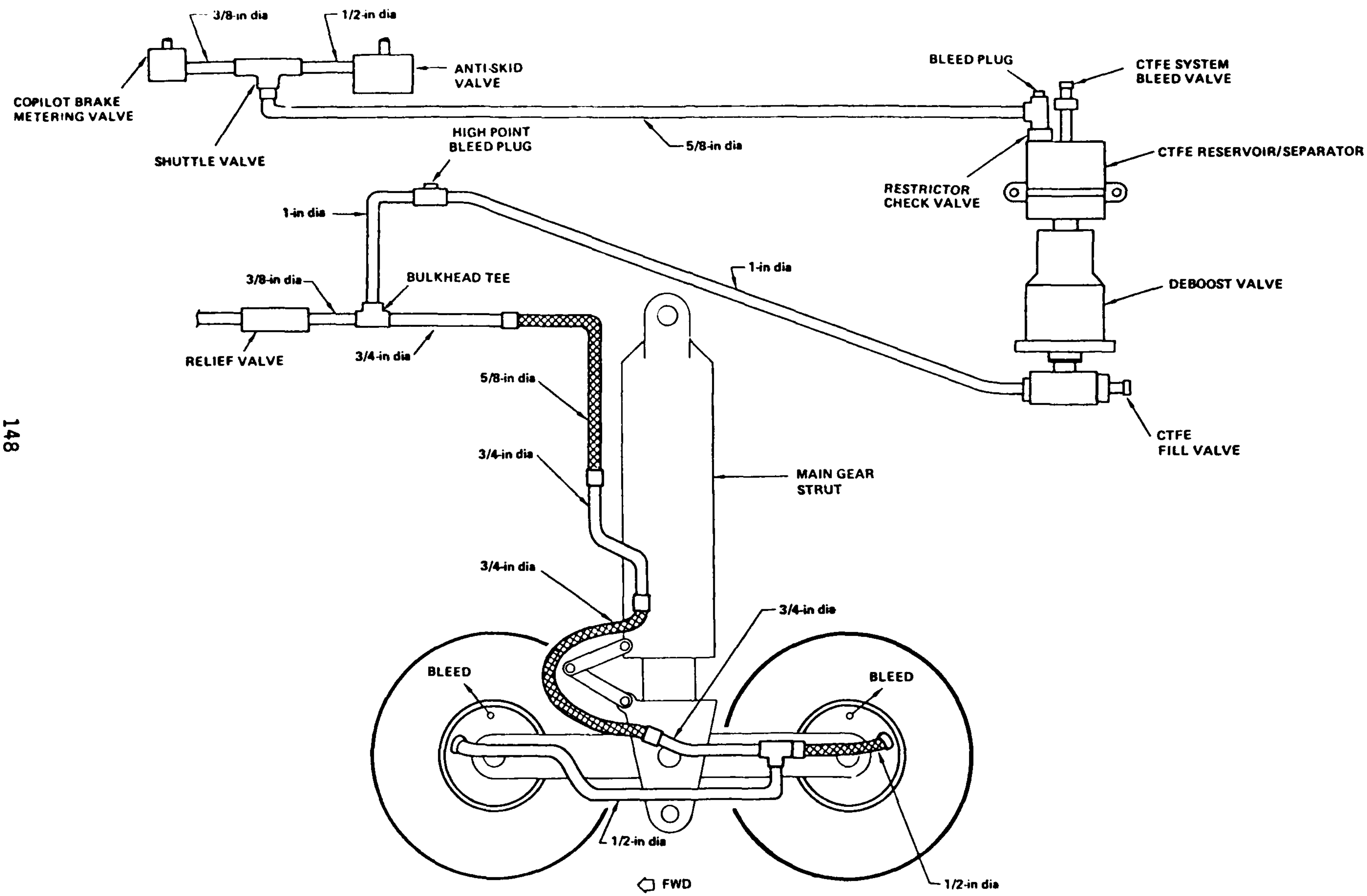


Figure B.1. FHBS Recommended System Configuration

APPENDIX C

SYSTEM FLIGHTWORTHINESS TEST PLAN

This appendix contains in total the planning document for the system flightworthiness testing, Revision A, dated December 7, 1984.

The page, figure, and table numbers have been changed from those in the document previously delivered to the USAF to be compatible with the format of this report.

FIREPROOF HYDRAULIC BRAKE SYSTEM

Contract F33615-83-C-2322

CDRL 5

System Flightworthiness Test Plan

November 27, 1984
Revision A - December 7, 1984

Prepared for:
Air Force Wright Aeronautical Laboratories
Aero Propulsion Laboratory

Attention: Mr. W. B. Campbell, AFWAL/POOS

Prepared by: D.W. Huling
D. W. Huling

Approved by: M. L. Holmdahl
M. L. Holmdahl
Program Manager

1.0 Introduction

The test outlined herein meets the requirements specified in section 4, paragraphs 4.3 and 4.10 through 4.13 of contract F33615-83-C-2322.

1.1 Background

A previous program contract F33615-80-C-2026 - Fireproof Hydraulic Brake System (FHBS) established the feasibility of using a Chlorotrifluoroethylene (CTFE) nonflammable hydraulic fluid in a two-fluid brake system for the C/KC-135 aircraft. The two-fluids were separated within the brake deboost valve. Flightworthiness of the system and/or equipment was not determined.

The current program requires component and system analyses and test with delivery of a flightworthy kit and qualification documentation. To avoid several inherent performance problems with the fluid-separating deboost valve, a new design using a reservoir/separator was recommended by Boeing and accepted by the Air Force. Most of the FHBS components are structurally unmodified, existing system components or MS (Military Standards), therefore, these components will be given a typical production parts acceptance test consisting of proof pressure and leakage tests at ambient temperature. The reservoir/separator, a totally new component, and the Fireproof Hydraulic Brake System will be qualification tested to show flightworthiness per MIL-W-5013.

1.1.1 FHBS Component Tests

The FHBS Component Test Plan (CDRL5) described the individual component flightworthiness and acceptance testing to be performed. The plan defines much of the component qualification testing to be accomplished during the system testing. This procedure is cost effective as well as duplicates the actual C/KC-135 installation duty cycling.

1.1.2 Baseline Tests

The FHBS contract requires braking performance equivalent to the existing C/KC-135/MIL-H-5606 brake system. In order to show equivalency, an accurate set of data must be available to use as a baseline for comparison. The current contract will determine baseline brake performance data from an accurate mockup of the C/KC-135 brake system.

1.2 Test Objectives

The conversion of a conventional single-fluid hydraulic brake system to a two-fluid system can effect both the dynamic response of the hydraulic system and the stopping performance of the aircraft. Factors such as additional seal friction, fluid viscosity, fluid density and fluid bulk modulus can change the dynamic response of the system thus effecting the stopping performance of the aircraft. The effects which these factors have can be minimized or even eliminated by adjusting hydraulic line sizes and restrictions. It is the objective of the system test to 1) demonstrate the performance equivalency of the new two-fluid brake system to the existing single-fluid brake system, and 2) demonstrate flightworthiness of the new and modified components.

1.3 Test Facility

The system tests will be performed using the C/KC-135 aircraft and brake control simulation. The simulation includes a digital-analog computer model of the aircraft and landing gear system and a hardware mockup of the brake control system.

The hydraulic brake system testing and brake performance evaluation task will be performed in the Boeing Hybrid Brake Control Laboratory (HYBCOL) located at the Boeing Developmental Center, Seattle, Washington. The primary functions of this facility are to develop new landing gear and brake control system concepts, and to checkout, tune, and predict the performance of existing braking systems.

The laboratory incorporates analog and digital computers and actual aircraft hardware. The HYBCOL enables the user to simulate, in real time, the response of an aircraft and its brake control system. The digital and analog computers contain mathematical models of aircraft rigid body and landing gear dynamics which interface with the hydraulic brake system mockup and antiskid control system that form the hardware elements within the facility. An overall interfacing schematic of the laboratory equipment is shown in Figure C.1.

The HYBCOL is presently supported by three Denelcor Model Ci-450 Analog/Hybrid computers, a Data General Digital minicomputer, a Nova 3 minicomputer, analog to digital and digital to analog converters, a CRT, line printer and other peripheral equipment. Figure C.2 shows the relationships and communication links between the elements within the simulator. The airplane simulation is divided between the analog and digital computers, with all high frequency responsive components modeled on the analog and low frequency responsive components modeled on the digital computer. This division increases the operational efficiency and flexibility which can be achieved. Figure C.3 shows a pictorial view of the digital minicomputer system while Figure C.4 shows the analog computers.

2.0 "As-Is" (Baseline) C/KC-135 Brake System Lab Test

2.1 Test objective

This test plan will provide the baseline data of the existing C/KC-135 brake system performance. The testing will include frequency and step response performance; constant and stepped friction stopping performance; and landing gear stability; and high, low and intermediate temperature performance of the C/KC-135 system using MIL-H-5606 hydraulic fluid.

2.2 Test Setup Description

2.2.1 System Hardware

The "as-is" C/KC-135 brake system test will be accomplished on a lab mockup system that is a "2-D" representation of the "3-D" actual system. The mockup will contain an exact duplication of tube diameters and lengths; fitting sizes and location; hose length, type, and size; and tube bends at the correct locations. The tubes will have the correct bend angles, bend radii and straight lengths between bends. The system installation is flattened to allow easier mounting and minimize the volume required for the environmental testing enclosure.

The C/KC-135 Mark II/five rotor brakes and antiskid controller will be used in the system test. The system tests will also utilize the C/KC-135 aircraft and brake control electronic simulator. The simulator includes a digital-analog computer model of the aircraft and landing gear structural springs. A schematic of the simulator showing its interface with the hardware mockup (Figure C.5) is presented in Figures C.1 and C.2.

2.2.2 Test Instrumentation

The "as-is" C/KC-135 brake system test instrumentation transducers and their location are identified in Figure 5. The range, accuracy, and resolution required for each piece of equipment used for data acquisition are listed in Table C.1.

2.2.3 Ancillary Equipment

The hydraulic power test bench will provide MIL-H-5606 hydraulic fluid flow to the brake system at normal system pressure of 3000 psi. High and low temperature tests will be conducted with the brake system within a thermally controlled environment chamber.

2.3 Proof Pressure and Leakage Tests

2.3.1 Setup

Following component acceptance testing and assembly of the brake test system, the system will be pressurized by the MIL-H-5606 hydraulic power bench to determine fluid system and pressurized component structural integrity. The relief valve will be removed and the line blocked for the proof pressure and leakage test. The accumulator precharge schedule is shown in Figure C.6.

The test system will be filled and bled as follows:

1. Pressurize the hydraulic power bench system to 500 ± 50 psi.

2. Apply brakes by positioning the manual valve.

3. Open the brake bleeding valve on the aft brake (whose system connection is a hose) assembly and bleed approximately one pint of fluid. Close bleeding valve.

4. Depressurize the hydraulic bench.

5. Repressurize system with the hydraulic bench to 500 ± 50 psi.

6. Open the brake bleeding valve on the forward brake (whose system connection is a tube) and bleed approximately one pint of fluid. Close bleeding valve.

7. Bleed the line leading to brake relief valve by loosening line plug fitting until fluid flows from line. Tighten the plug fitting with fluid still flowing.

8. Depressurize the hydraulic bench.

9. Raise the hydraulic bench pressure to 3000 psi.

10. Energize/de-energize cycle the antiskid valve for at least one minute to bleed air from the antiskid valve.

11. Apply and release the manual brake valve five times to move the brake pressure plates against the heat stacks. Release brakes completely between applications allowing the pressure plates to fully retract. Wait 30 seconds between applications. On the final application hold enough pressure to keep the pressure plates against the heat stacks and bleed two to three ounces of fluid from each brake.

12. Depressurize hydraulic power supply bench.

13. Connect a hand pump type hydraulic pressure source to the aft wheel brake and submerge forward brake bleed hose end into a container of hydraulic fluid. Apply hydraulic pressure with both bleed fittings open. Close the forward bleed fitting when the fluid flows free of air. Apply pressure of 50 to 80 psi and pump not less than one gallon of MIL-H-5606 hydraulic fluid into the line. Close the aft brake bleed valve.

14. Pressurize the brake system with the hydraulic power bench to 3000 psi and exercise the brake manual valve several times to insure all the air is out of the system.

15. Remove hose from bleed fittings and replace dust caps.

2.3.2 Test Conditions

The brake system will be proof pressure tested to 4500 psi (1500 psi on the system below the deboost valve) for five minutes minimum at room temperature and pressure.

The brake system will be subjected to 25 cycles of the application and release of maximum supply pressure (3000 psi). The brake pistons will be allowed to return to an equilibrium position after each release of pressure and prior to reapplication of pressure. The time required for the brake piston to reach an equilibrium position will be noted.

2.3.3 Test Data

The following data will be measured and recorded at the beginning, middle and end of the five minute test period and during the 25 full pressure cycles.

Fluid leakage external to the system at the following locations:

- Brake pistons
- Deboost valve
- Tube connections
- Component port fittings

Readings for hydraulic supply pressure, antiskid valve brake pressure and forward brake pressure

2.3.4 Acceptance Criteria

There will be no leakage from the system sufficient to form a drop during the proof pressure test. Leakage at dynamic seals during the brake cycling shall not exceed one drop of fluid per each 3 inches of peripheral seal length. The brake pistons shall return to the fully retracted position after each release of pressure.

2.4 Room Temperature Performance Tests

Brake system performance tests will first be conducted at ambient laboratory conditions. The tests shall include frequency response, step response, constant friction runway stopping distance, step friction runway stopping distance and landing gear stability.

2.4.1 Test Setup

The performance test setup will be that described in paragraphs 2.2.1, 2.2.2, and 2.2.3. The accumulator precharge pressure will be checked for the pressure shown in Figure C.6. The brake relief valve will be checked for 1200 ± 30 psi cracking pressure and installed in the system. (Bleed the relief valve line following installation.)

2.4.2 Test Data

All data noted in Tables C.2 and C.3 will be measured and recorded for each test condition. Each condition will be run three times.

2.4.3 Acceptance Criteria

These baseline tests will serve as the basis for comparison to the later FHBS test data. Acceptable data will be that which is easily read and reproducible for reporting purposes.

2.4.4 Test Criteria

2.4.4.1 Frequency Response

A D.C. electrical control signal corresponding to the desired nominal pressure level (Table C.2) of the test will be applied to the antiskid valve. A 0.5 Hertz sinusoidal electrical control signal will be superimposed on top of the DC signal. The amplitude of the sinusoidal electrical signal will be adjusted until the Table C.2 pressure amplitude at the brake is obtained. The frequency of the sinusoidal signal will then be varied between 0.5 Hertz and 50 Hertz. The gain and phase angle of the system and components, will be determined as a function of frequency for the pressure conditions specified in Table C.2. The tests will be performed at laboratory ambient conditions.

2.4.4.2 Step Response

A D.C. electrical control signal corresponding to the initial test pressure level will be applied to the antiskid valve. The control signal will then be stepped up or down to a level corresponding to the final test pressure level desired after all transients have damped out. Time history plots of the control signal and test pressures as defined in Table C.3 will be recorded. The tests will be performed at laboratory ambient conditions.

2.4.4.3 Constant Friction Runway Stopping Performance

This test will determine the stopping performance of the aircraft in terms of rollout distance under normal runway conditions. During this test, braking will be initiated at a typical brake application velocity ($\approx$200 feet per second) 2.0 seconds following simulated touchdown and continued until the aircraft decelerates to a typical turnoff velocity of 24 feet per second. The peak available ground friction coefficient (mu) will be held at a constant value throughout the entire run. The distance travelled from brake application to turnoff will be recorded. Runway friction coefficients of .6, .5, .4, .3, .2 and .1 will be utilized in the conduct of this test.

2.4.4.4 Step Friction Runway Stopping Performance

The step friction test is designed to determine the adaptability of the brake control system to rapidly changing runway friction conditions. During this test, braking will be initiated at a typical brake application velocity ($\approx$200 feet per second) 2.0 seconds following simulated touchdown and

continue until the aircraft decelerates to a typical brake application velocity of 24 feet per second. The peak available ground friction coefficient will be made to vary in step fashion as shown in Figure C.7. Several step changes will be made during the braking run, so that system operation can be observed under a variety of conditions. The distance travelled from brake application to turnoff will be recorded.

2.4.4.5 Landing Gear Stability Test

The stability test is designed to measure the ability of the brake control system to contribute to the fore and aft vibrational stability of the landing gear. The stability margin of the system will be determined by establishing the amount of strut damping required for stable landing gear oscillations.

During a normal braking run, the landing gear strut will be made to oscillate by increasing the brake torque to 1.5 times its normal value for a short period of time (i.e. a brake torque impulse). The brake torque impulses will be applied at various velocities so the strut oscillations can be observed at a variety of conditions. The strut damping coefficient will be lowered until the landing gear oscillations are no longer damped, the brake system goes unstable or strut damping is zero. The strut displacement as a function of time will be recorded in addition to the strut damping ratio.

2.5 Maximum Temperature (160^{o}F) Performance Tests

The maximum temperature performance tests will determine the brake system performance for frequency and step responses, constant and stepped friction runway stopping distances and landing gear stability at 160^{o}F fluid temperature.

2.5.1 Test Setup

The test system (as shown schematically in Figure C.5) will be the same as utilized in the tests of section 2.4 - Room Temperature Performance Tests. An environmental chamber capable of maintaining 160^{o}F will enclose the test system.

2.5.2 Test Data Requirements

The data required by paragraph 2.4.2 will be taken. In addition, the ambient and fluid temperature will be taken continuously.

2.5.3 Acceptance Criteria

These baseline tests will serve as the basis for comparison to the later FHBS test system data. Acceptable data shall be that which is easily read and reproducible for reporting purposes.

2.5.4 Test Conditions

The maximum temperature performance tests will be conducted after the test system has heat soaked for a minimum of eight hours at 165 ± 5°F. The environmental temperature shall be maintained in this range during conduct of the tests.

2.5.4.1 Frequency Response

The frequency response testing shall be conducted per the requirements of paragraph 2.4.4.1, except the hydraulic fluid temperature shall be 160 ± 5°F.

2.5.4.2 Step Response

The step response testing will be conducted per the requirements of paragraph 2.4.4.2, except the fluid temperature shall be 160 ± 5°F.

2.5.4.3 Constant Friction Runway Stopping

The constant friction runway stopping performance tests will be conducted per the requirements of paragraph 2.4.4.3, except the fluid temperature shall be 160 ± 5°F.

2.5.4.4 Stepped Friction Runway Stepping

The stepped friction runway stopping performance tests will be conducted per the requirements of paragraph 2.4.4.4, except the fluid temperature shall be 160 ± 5°F.

2.5.4.5 Landing Gear Stability

The landing gear stability tests will be conducted per the requirements of paragraph 2.4.4.5, except the fluid temperature shall be 160 ± 5°F.

2.6 Minimum Temperature (-65°F) Performance Tests

The minimum temperature performance tests will determine the brake system performance for frequency and step responses, and constant friction runway stopping distances at system temperature of -65°F. In the event of excessive seal leakage during the minimum temperature tests, the temperature will be raised until leakage no longer occurs and the testing continued.

2.6.1 Test Setup

The test system (as shown schematically in Figure 5) will be the same as utilized in the Room Temperature Performance Tests of section 2.4. An environmental chamber capable of maintaining -65°F will enclose the test system.

2.6.2 Test Data Requirements

The data required by paragraph 2.4.2 will be taken. In addition, the ambient temperature will be taken continuously.

2.6.3 Acceptance Criteria

The room temperature performance tests will result in data that will be utilized to show braking/stopping distance equivalency. Acceptable data will be that which is easily read and reproducible for reporting purposes.

2.6.4 Test Conditions

The minimum temperature performance tests will be conducted after the test system has cold soaked for a minimum of eight hours at -70 ± 5F. The environmental temperature shall be maintained in this range during conduct of the tests.

2.6.4.1 Frequency Response

The frequency response testing shall be conducted per the requirements of paragraph 2.4.4.1, except the hydraulic fluid temperature shall be -65 ± 5^{o}F.

2.6.4.2 Step Response

The step response testing will be conducted per the requirements of paragraph 2.4.4.2, except the hydraulic fluid temperature shall be -65 ± 5^{o}F.

2.6.4.3 Constant Friction Runway Stopping Distance

The constant friction runway stopping performance tests will be conducted per the requirements of paragraph 2.4.4.3, except the hydraulic fluid temperature will be -65 ± 5^{o}F.

2.6.4.4 Stepped Friction Runway Stepping

The stepped friction runway stopping performance tests will be conducted per the requirements of paragraph 2.4.4.4, except the hydraulic fluid temperature will be -65 ± 5^{o}F.

2.6.4.5 Landing Gear Stability

The landing gear stability tests will be conducted per the requirements of paragraph 2.4.4.5, except the fluid temperature shall be -65 ± 5^{o}F.

3.0 FHBS/KC-135 Brake System Performance Tests

3.1 Test Objectives

This test plan provides for a demonstration of the FHBS maintainability and performance flightworthiness through a series of tests that will evaluate fill and bleed procedure; reservoir servicing; proof pressure; static and dynamic seal leak checks; frequency and step response performances; constant and step friction stopping performance; landing gear stability; and high, low and intermediate temperature performance.

3.2 Test Setup Description

3.2.1 System Hardware

The FHBS testing will be accomplished on a lab mockup of actual aircraft hardware and a simulated plumbing system. Figure C.8 schematically shows the major components that make up the two-fluid system, except initially the restrictor/check valve will not have its poppet nor retainer. The plumbing system shall be a "2-D" representation of the "3-D" actual system. The FHBS mockup will contain the new design for tube diameters and lengths, fittings, and hoses, as well as the "As Is" system components and reservoir/separator. The C/KC-135 five rotor brakes cleaned and resealed with modified PNF elastomers will be used in the FHBS tests.

The C/KC-135 Mark II brake antiskid controller will be used in the system tests. No adjustment to the electronics is anticipated.

The FHBS testing will utilize the C/KC-135 aircraft and Mark II brake control electronic simulator. The simulator includes a digital-analog computer model of the aircraft and landing gear structural springs. A schematic of the simulator showing its interface with the hardware mockup is presented in Figure C.1.

3.2.2 Test Instrumentation

The FHBS/KC-135 brake system test instrumentation transducers and their location are identified in Figure C.8. The range, accuracy and resolution required for each piece of equipment used for data acquisition are listed in Table C.1.

3.2.3 Ancillary Equipment

The hydraulic power test bench will provide MIL-H-5606 hydraulic fluid flow to the brake system at normal system pressure of 3000 psi. High and low temperature tests will be conducted with the brake system within a thermally controlled environment chamber.

3.3 Maintenance Demonstration Tests

A maintenance demonstration test will be performed to show the acceptability of the two-fluid system fill and bleed procedures and CTFE reservoir level servicing.

3.3.1 Setup

Following component acceptance testing and assembly of the FHBS test system, the MIL-H-5606 power cart will be connected to the system.

The CTFE reservoir servicing cart will be checked for a fluid quantity of at least five gallons of CTFE/AO-2 hydraulic fluid.

NOTE: Prior to starting the fill and bleed demonstration test below, no hydraulic (CTFE nor MIL-H-5606) fluid will be put into the components or plumbing system.

The brake relief valve shall be removed from the system and the line blocked.

3.3.2 Test Data

The following test data will be measured and recorded.

Bleeding and CTFE reservoir servicing time, and volume of fluid expelled with bubbles and without bubbles.

3.3.3 Acceptance Criteria

The evaluation of the fill and bleed, and reservoir servicing is designed to provide data for the development of the Technical Order (T.O.) for FHBS maintenance procedures. Should the proposed procedures prove to require excessive time or fluid volume to properly complete the applicable task, redesign of the system and/or rewriting of the procedure will be accomplished, and the test rerun.

3.3.4 Test Conditions

3.3.4.1 System Filling and Bleeding (see Figure C.9)

A MIL-H-5606 power supply bench shall be connected to the appropriate interface. The bench shall be energized for an output pressure of 100 psi. Fluid will be introduced to the test system and allowed to flow (Pilot Metering Valve in "brake" position) for five minutes. Open the bleed fitting just above the reservoir/separator, and close when the hydraulic fluid flows without air bubbles. Cycle the servovalve for 25 cycles and reopen the bleed fitting above the reservoir/separator till the fluid flows without air bubbles. Reduce the bench pressure to zero.

NOTE: A time record (to the minute) of the following activity shall be logged, as well as measure and record all bleed fluid volume.

Connect the CTFE service cart to the forward brake bleed fitting (brake with a tube) and open the aft brake bleed fitting. Pump CTFE fluid into the system until fluid flows from the aft wheel bleed fitting then close the bleed fitting. Remove the service cart from the forward brake fitting. Disconnect the aft brake hose and connect the service cart to the hose. Open the forward brake bleed fitting and pump CTFE fluid into the system until the bleed fluid

flows free of air. Close the forward brake bleed fitting, then open the bleed fitting near the bulkhead tee and continue to pump CTFE into the system. When fluid, free of air bubbles, starts to flow from the bleed fitting, close it. Reconnect the brake hose to the brake and connect the fill cart to the CTFE system fill valve just under the deboost valve. Pump in CTFE fluid until reservoir/separator level is 100%. Remove the cap from the CTFE system bleed valve at the end of the reservoir/separator rod, connect a drain tube and open valve.

Open the bleed fitting near the bulkhead fitting. Pump in CTFE fluid until fluid free of air bubbles starts to drain from either location then close that fitting and continue to fill system until fluid, free of air bubbles, flows from the other fitting then close it. Close the fill valve.

Energize the MIL-H-5606 power supply to 500 psi, open the manual brake valve and cycle the antiskid valve for 25 cycles. Bleed the forward brake, then the aft brake, then the bleed plug near the bulkhead tee and last the reservoir/separator bleed valve. Reduce the supply pressure to zero. Record the reservoir level then replenish/reduce the CTFE reservoir to 80%. After five minutes minimum, re-energize the supply bench to 500 psi and repeat this paragraph until no air exits with bleed fluid.

3.3.4.2 Reservoir/Separator Servicing

Energize the MIL-H-5606 hydraulic power supply bench to 100 psi, put brake metering valve in brake position and drain 300 ml. of CTFE fluid from the system (Retain the drained fluid in a clean sample bottle). Reduce the supply bench pressure to zero. Return the system configuration to normal (dust caps on, etc.).

While keeping an accurate (± 2 seconds) time record, remove the CTFE system fill valve dust cap, connect the CTFE service cart hose to the fill valve and open valve. Note the reservoir/separator level and pump in fluid until reservoir level reaches 80%. Close fill valve, disconnect service cart and install the fill valve dust cap.

3.4 Proof Pressure and Leakage Tests

The test system will be pressurized by the MIL-H-5606 hydraulic power supply bench to determine fluid system and pressurized component structural integrity.

3.4.1 Setup

Service the brake system accumulator to the precharge pressure of Figure C.6. The CTFE system shall be bled of air and filled to the 80% reservoir/separator level. Ascertain the CTFE system relief valve has been removed and the system connection capped. Set the brake metering valve in the "brake" position.

3.4.2 Test Conditions

The brake system will be proof pressure tested to 4500 psi (1500 psi on the system below the deboost valve) for five minutes minimum at room temperature and pressure.

The brake system will be subjected to 25 cycles of the application and release of maximum supply pressure (3000 psi). The brake pistons will be allowed to return to an equilibrium position after each release of pressure and prior to reapplication of pressure position. The time required for the brake piston to reach an equilibrium position will be noted.

3.4.3 Test Data

The following data will be measured and recorded at the beginning, middle and end of the five minute test period and during the 25 full-pressure cycles:

Fluid leakage external to the system at the following locations:

- Brake Pistons
- Deboost Valve Vents
- Tube Connections
- Component Port Fittings
- Reservoir/Separator
- Fill Valve
- Bleed Fittings

Readings for hydraulic supply pressure, antiskid valve brake pressure, and forward brake pressure.

3.4.4 Acceptance Criteria

There will be no leakage from the system sufficient to form a drop during the proof pressure test. Leakage at dynamic seals during the brake cycling shall not exceed one drop of fluid per each 3 inches of peripheral seal length. The brake pistons shall return to the fully retracted position after each release of pressure.

3.5 Restrictor Check Valve Orifice Size Determination

Preliminary analysis has shown that the lower fluid velocities in the CTFE system coupled with the lower viscosity of the fluid produces a significant loss in coulomb damping which affects the stopping performance characteristic. A restrictor/check valve installed in the system modifies the response characteristic allowing FHBS equivalency with the existing single-fluid C/KC-135 Mark II brake system. Analysis has determined the restrictor orifice diameter to be 0.16 inch. However, these analysis have never proven to be very accurate. Therefore, a "cut and try" orifice diameter/stopping performance test will be accomplished on a series of restrictor diameters to determine the correct orifice size.

3.5.1 Test Setup

The test system will be as previously described in paragraph 3.2.1, 3.2.2, and 3.2.3. The initial test will be conducted with the poppet and retainer removed from the restrictor/check valve. The subsequent tests will use the restrictor/check valve poppet with orifice sizes per the following:

Orifice Diameter - Inch
.10
.125
.15
.175
.20
.225

In the event the stopping performance data for an orifice test is trending away from the baseline frequency response, subsequent orifice size test will be deleted.

3.5.2 Test Data

The following data will be measured and recorded for each orifice size test condition. Each test condition will be repeated three times.

Hydraulic Supply Pressure	Gage Reading
Metering Valve Pressure	Gage Reading
Brake Pressure	Time History

The brake pressure transducer signal is an input to an analog computer as shown in Figure C.2. The computer analyzes the pressure signal and creates real time outputs of brake torque, wheel speed, and antiskid valve current. These outputs will be recorded on a strip chart.

3.5.3 Acceptance Criteria

Each restrictor/check valve orifice size stopping performance test data will be compared to the "baseline" test data obtained in section 2.4. The restrictor orifice which gives the closest match to the "baseline" will be selected for the remainder of the system tests and the aircraft.

3.5.4 No Restrictor Test

The initial test to determine the proper orifice size will be accomplished utilizing the restrictor/check valve without its poppet and retainer installed. The stopping performance will be determined for a constant friction runway conditions of mu = .6, .5, .4, .3, .2, and .1.

3.5.5 Initial Restrictor Orifice Size Test

The poppet-less restrictor check valve will be removed and replaced with a restrictor/check valve whose poppet will have an orifice of a diameter based on a "best guess" following a comparison of the data from paragraphs 3.5.4 and 2.4.4.3. The stopping performance will be determined for a constant friction runway condition of mu = .6, .5, .4, .3, .2 and .1.

3.5.6 Second Restrictor Orifice Size Test

Based upon a comparison of the stopping performance data obtained in paragraphs 3.5.4, 3.5.5 and 2.4.4.3, a new orifice diameter for the restrictor/check valve poppet will be determined and tested per paragraph 3.5.5.

3.5.7 Third Restrictor Orifice Size Test (As Required)

Following a comparison of the stopping performance data obtained in paragraph 3.5.6 and 2.4.4.3, should the braking equivalency still not be satisfactory, a third restrictor orifice diameter will be determined and tested per paragraph 3.5.5.

3.6 Room Temperature Performance Tests

Brake system performance tests will first be conducted at ambient laboratory conditions. The tests will include frequency and step responses, constant and step friction runway stopping distances and landing gear stability.

3.6.1 Test Setup

The FHBS performance test setup will be that described in paragraphs 3.2.1, 3.2.2, and 3.2.3. The accumulator precharge pressure will be checked against the values in Figure C.6. The brake relief valve will be checked for 1200 ± 30 psi cracking pressure with CTFE fluid and installed in the system.

3.6.2 Test Data

All the data noted in Tables C.2 and C.3 shall be measured and recorded for each test condition. Each condition will be run three times.

3.6.3 Acceptance Criteria

The room temperature performance tests will result in data that will be utilized to show FHBS braking/stopping equivalency to the KC-135 single fluid system. Acceptable data will be that which is easily read and reproducible for reporting purposes.

3.6.4 Test Conditions

3.6.4.1 Frequency Response

A D.C. electrical control signal corresponding to the nominal pressure level of Table C.2 will be applied to the antiskid valve. A 0.5 Hertz sinusoidal electrical control signal will be superimposed on top of the nominal signal. The amplitude of the sinusoidal electrical signal will be adjusted until the Table C.2 pressure amplitude at the brake is obtained. The frequency of the sinusoidal signal will then be varied between 0.5 Hertz and 50 Hertz. The gain and phase angle of the system and components will be determined as a function of frequency, for the pressure conditions specified in Table C.2. The tests will be performed at laboratory ambient conditions.

3.6.4.2 Step Response

A D.C. electrical control signal corresponding to the initial test pressure level will be applied to the antiskid valve. The control signal will then be stepped up or down to a level corresponding to the final test pressure level desired after all transients have damped out. Time history plots of the control signal and test pressures as defined in Table C.3 will be recorded. The tests will be performed at laboratory ambient conditions.

3.6.4.3 Constant Friction Runway Stopping Performance

This test will determine the stopping performance of the aircraft in terms of rollout distance under normal runway conditions. During this test, braking will be initiated at a typical brake application velocity ($\approx$200 feet per second) 2.0 seconds following simulated touchdown and continue until the aircraft decelerates to a typical turnoff velocity of 24 feet per second. The peak available ground friction coefficient (mu) will be held at a constant value throughout the entire run. The distance travelled from brake application to turnoff will be recorded. Runway friction coefficients of .6, .5, .4, .3, .2 and .1 will be utilized in the conduct of this test.

3.6.4.4 Step Friction Runway Stopping Performance

The step friction test is designed to determine the adaptability of the brake control system to rapidly changing runway friction conditions. During this test, braking will be initiated at a typical brake application velocity ($\approx$200 feet per second) 2.0 seconds following simulated touchdown and continue until the aircraft decelerates to a typical brake application velocity of 24 feet per second. The peak available ground friction coefficient will be made to vary in step fashion as shown in Figure C.7. Several step changes will be made during the braking run, so that system operation can be observed under a variety of conditions. The distance travelled from brake application to turnoff will be recorded.

3.6.4.5 Landing Gear Stability

The stability test is designed to measure the ability of the brake control system to contribute to the fore and aft vibrational stability of the landing gear. The stability margin of the system will be determined by establishing

the amount of strut damping required for stable landing gear oscillations. During a normal braking run the landing gear strut will be made to oscillate by increasing the brake torque to 1.5 times its normal value for a short period of time (i.e. a brake torque impulse). The brake torque impulses will be applied at various velocities so the strut oscillations can be observed at a variety of conditions. The strut damping coefficient will be lowered until the landing gear oscillations are no longer damped, the brake system goes unstable or strut damping is zero. The strut displacement as a function of time will be recorded in addition to the strut damping ratio.

3.7 Maximum Temperature (160°F) Performance Tests

The maximum temperature performance tests will determine the brake system performance of frequency and step responses, constant and stepped friction runway stopping distances and landing gear stability at 160°F fluid temperature.

3.7.1 Test Setup

The test system (as shown schematically in Figure C.8) will be the same as utilized in the Room Temperature Performance Tests of section 3.6. An environmental chamber capable of maintaining 165°F will enclose the test system.

3.7.2 Test Data Requirements

The data required by paragraph 3.6.2 will be taken. In addition, the ambient and fluid temperatures will be taken continuously.

3.7.3 Acceptance Criteria

The maximum temperature performance tests will result in data that will be utilized to show braking/stopping distance equivalency. Acceptable data will be that which is easily read and reproducible for reporting purposes.

3.7.4 Test Conditions

The maximum temperature performance tests will be conducted after the test system has heat soaked for a minimum of eight hours at 165 ± 5°F. The environmental temperature shall be maintained in this range during conduct of the tests.

3.7.4.1 Frequency Response

The frequency response testing shall be conducted per the requirements of paragraph 3.6.4.1, except the hydraulic fluid temperature shall be 160 ± 5°F.

3.7.4.2 Step Response

The step response testing will be conducted per the requirements of paragraph 3.6.4.2, except the hydraulic fluid temperature shall be 160 ± 5°F.

3.7.4.3 Constant Friction Runway Stopping Performance

The constant friction runway stopping performance tests will be conducted per the requirements of paragraph 3.6.4.3, except the hydraulic fluid temperature will be 160 ± 5°F.

3.7.4.4 Stepped Friction Runway Stopping

The stepped friction runway stopping performance tests will be conducted per the requirements of paragraph 3.6.4.4, except the hydraulic fluid temperature will be 160 ± 5°F.

3.7.4.5 Landing Gear Stability

The landing gear stability tests will be conducted per the requirements of paragraph 3.6.4.5, except the temperature shall be 160 ± 5°F.

3.8 Minimum Temperature (-65°F) Performance Tests

The minimum temperature performance tests will determine the brake system performance for frequency and step resposnes, and constant friction runway stopping distances at system temperature of -65°F. In the event of excessive seal leakage during the minimum temperature tests, the temperature will be raised until leakage no longer occurs and the testing continued.

3.8.1 Test Setup

The test system (as shown schematically in Figure C.8) will be the same as utilized in the Room Temperature Performance Tests of section 3.6. An environmental chamber capable of maintaining -70°F will enclose the test system.

3.8.2 Test Data Requirements

The data required by paragraph 3.6.2 will be taken. In addition, the ambient and fluid temperatures will be taken continuously.

3.8.3 Acceptance Criteria

The minimum temperature performance tests will result in data that will be utilized to show braking/stopping distance equivalency. Acceptable data will be that which is easily read and reproducible for reporting purposes.

3.8.4 Test Conditions

The minimum temperature performance tests will be conducted after the test system has cold soaked for a minimum of eight hours at -70 ± 5F. The environmental temperature shall be maintained in this range during conduct of the tests.

3.8.4.1 Frequency Response

The frequency response testing shall be conducted per the requirements of paragraph 3.6.4.1, except the hydraulic fluid temperature shall be -65 ± 5°F.

3.8.4.2 Step Response

The step response testing will be conducted per the requirements of paragraph 3.6.4.2, except the hydraulic fluid temperature shall be -65 ± 5°F.

3.8.4.3 Constant Friction Runway Stopping Distance

The constant friction runway stopping performance tests will be conducted per the requirements of paragraph 3.6.4.3, except the hydraulic fluid temperature will be -65 ± 5°F.

3.8.4.4 Stepped Friction Runway Stopping

The stepped friction runway stopping performance tests will be conducted per the requirements of paragraph 3.6.4.4, except the hydraulic fluid temperature will be -65 ± 5°F.

3.8.4.5 Landing Gear Stability

The landing gear stability tests will be conducted per the requirements of paragraph 3.6.4.5, except the temperature shall be -65 ± 5°F.

3.9 Intermediate Temperature Performance Tests

Immediately following the low temperature test, the test system will be warmed rapidly to a temperature of 160°F. While the temperature is being raised, the system will be performance checked at maximum increments of 36°F to determine satisfactory operation throughout the temperature range. These check tests will be made without waiting for temperature of the entire system to stabilize. In conjunction with this testing, icing tests will also be performed.

3.9.1 Test Setup

The test hardware, instrumentation and environmental chamber will be that used in section 3.8.

3.9.2 Test Data Requirements

The data requirements will be identical to paragraph 3.8.2 except with the addition of visual inspection data for the icing test.

3.9.3 Acceptance Criteria

The acceptance criteria will be identical to paragraph 3.8.3 except with the additional requirement of no reduction in performance due to icing of the

reservoir/separator. The reservoir/separator rod and pressure traces shall show no significant evidence of sticking nor fluid leakage (such as caused by ice getting through the rod scraper ring).

3.9.4 Test Conditions

The intermediate temperature performance tests will be initiated immediately following the minimum temperature tests of section 3.8. The FHBS reservoir/separator will be coated with ice by spraying on water at the initiation of the warmup (-65°F) and following each performance check (-30°F, 0°F, and 30°F). The test system will be warmed as rapidly as possible by initially energizing the environmental chamber's heater and opening the doors/lids of the chamber. Following the 30°F performance check, the chamber doors/lids will be closed.

Performance checks will be taken at -30°F, 0°F, 30°F, 60°F and 125°F. The check will consist of a single frequency response scan.

3.9.4.1 Frequency Response Scan

A D.C. electrical control signal corresponding to the 325 psi brake pressure level of the test will be applied to the antiskid valve. A 0.5 Hertz sinusoidal electrical control signal will be superimposed on top of the DC signal. The amplitude of the sinusoidal electrical signal will be adjusted until ±100 psi pressure amplitude at the brake is obtained. The frequency of the sinusoidal signal will be varied between 0.5 and 50 Hertz. The gain and phase angle of the system and components will be recorded as a function of frequency, for the pressure conditions specified in Table C.2.

4.0 FHBS/KC-135 Brake System Endurance Tests

The FHB System will be endurance cycled to show flightworthiness durability.

4.1 Test Objectives

This test plan provides for a demonstration of the FHB System's endurance flightworthiness through a series of tests that will evaluate the normal and maximum cycling and materials compatibility.

4.2 Test Setup Description

The FHB System test hardware, instrumentation and ancilliary equipment will be identical to that utilized in the section 3.0 system performance tests, and incorporate a counter to record the number of endurance cycles as well as a square-wave signal generator to provide the antiskid valve a proper signal.

4.3 Endurance Testing

4.3.1 Test Data Requirements

The following test data will be measured and recorded.

- Continuous recordings of brake pressure and servovalve signal.
- Periodic fluid leakage inspections will be made and the total leakage recorded.
- Cycle counter.

300 ml. CTFE and MIL-H-5606 fluid samples will be taken from the FHB System prior to endurance cycling, at 50,000 and 100,000 normal operation cycles, and at the end of the 5,000 maximum operating pressure cycles. An 8 ounce CTFE fluid sample will be sent to the Air Force Project Engineer and the remaining fluid samples to the Boeing Materials Technology (BMT) Lab. The BMT samples will be analyzed for kinematic viscosity at 100°F and water content, and by a visual inspection to determine change in color, precipitation, etc.

4.3.2 Acceptance Criteria

The endurance testing is designed to show a life expectancy that exceeds the flight testing cycles and, therefore, shows the flightworthiness of the FHBS.

If a component fails during these tests, the component, test data, and hydraulic fluid will be analyzed to determine the cause of the failure.

Modifications as dictated by the failure will be proposed to AFWAL to correct the deficiency with estimated cost and schedule changes. Written concurrence from the AFWAL project engineer will be obtained before any component modification is made.

During and at the conclusion of the test, the leakage rate will be limited as specified in paragraph 3.4.4.

4.3.3 Test Conditions

The FHBS will be subjected to 100,000 cycles of application and release of pressure equal to normal operating pressure, and 5000 cycles at a pressure equivalent to the maximum operating pressure. The rate of cycling shall not be greater than 30 cycles per minute. The electrical signal to the antiskid valve will be square waved.

4.3.4 Endurance Cycling

The FHBS endurance cycling will be accomplished utilizing the antiskid valve to apply the pressure cycles.

4.3.4.1 Normal Pressure Endurance Cycle Test

The FHBS normal pressure endurance cycling will consist of 100,000 square-wave pressure cycles to a pressure of 1500 psi (above the deboost valve) at a rate of 30 cpm. Fluid samples will be taken prior to testing, at 50,000 cycles and at 100,000 cycles.

4.3.4.2 Maximum Pressure Endurance Cycle Test

The FHBS maximum pressure endurance cycling will consist of 5000 square-wave pressure cycles to a pressure of 3000 psi (above the deboost valve) at a rate of 30 cpm. A fluid sample will be taken at the conclusion of testing.

5.0 Post Test Hardware Inspection

The functional components of the FHBS will be disassembled and inspected following the testing described above. The inspection will examine all parts subjected to wear for unusual wear patterns. Photographs will be taken of all parts.

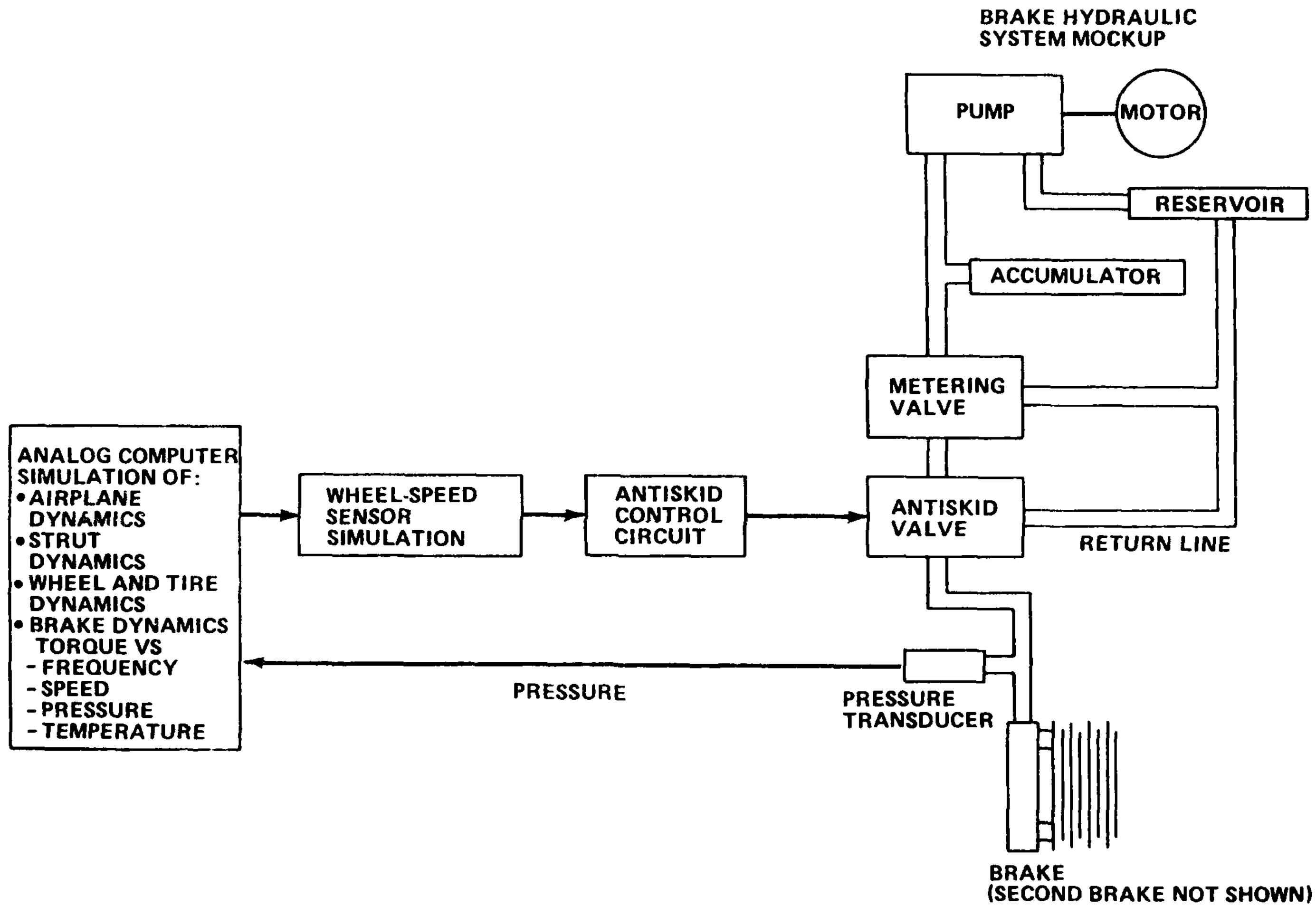


Figure C.1. Test Setup – System Performance Testing, Hybrid Computer Simulation

AD-A163 542 FIREPROOF HYDRAULIC BRAKE SYSTEM(U) BOEING MILITARY 3/4
AIRPLANE CO SEATTLE WA D W HULING ET AL. OCT 85
AFWAL-TR-85-2072 F33615-83-C-2322

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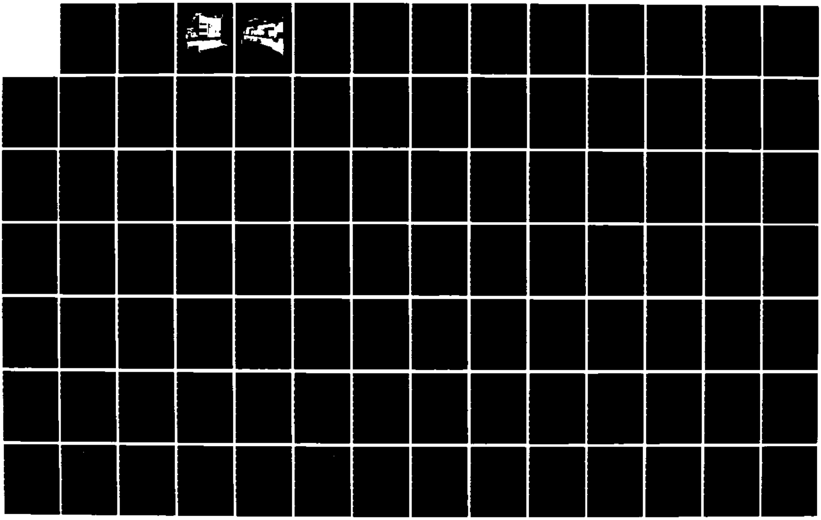

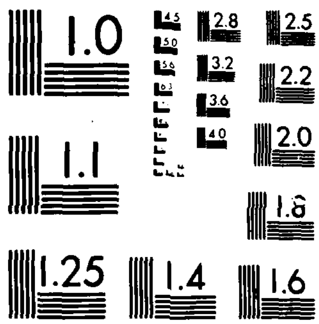
1.0
1.1
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1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

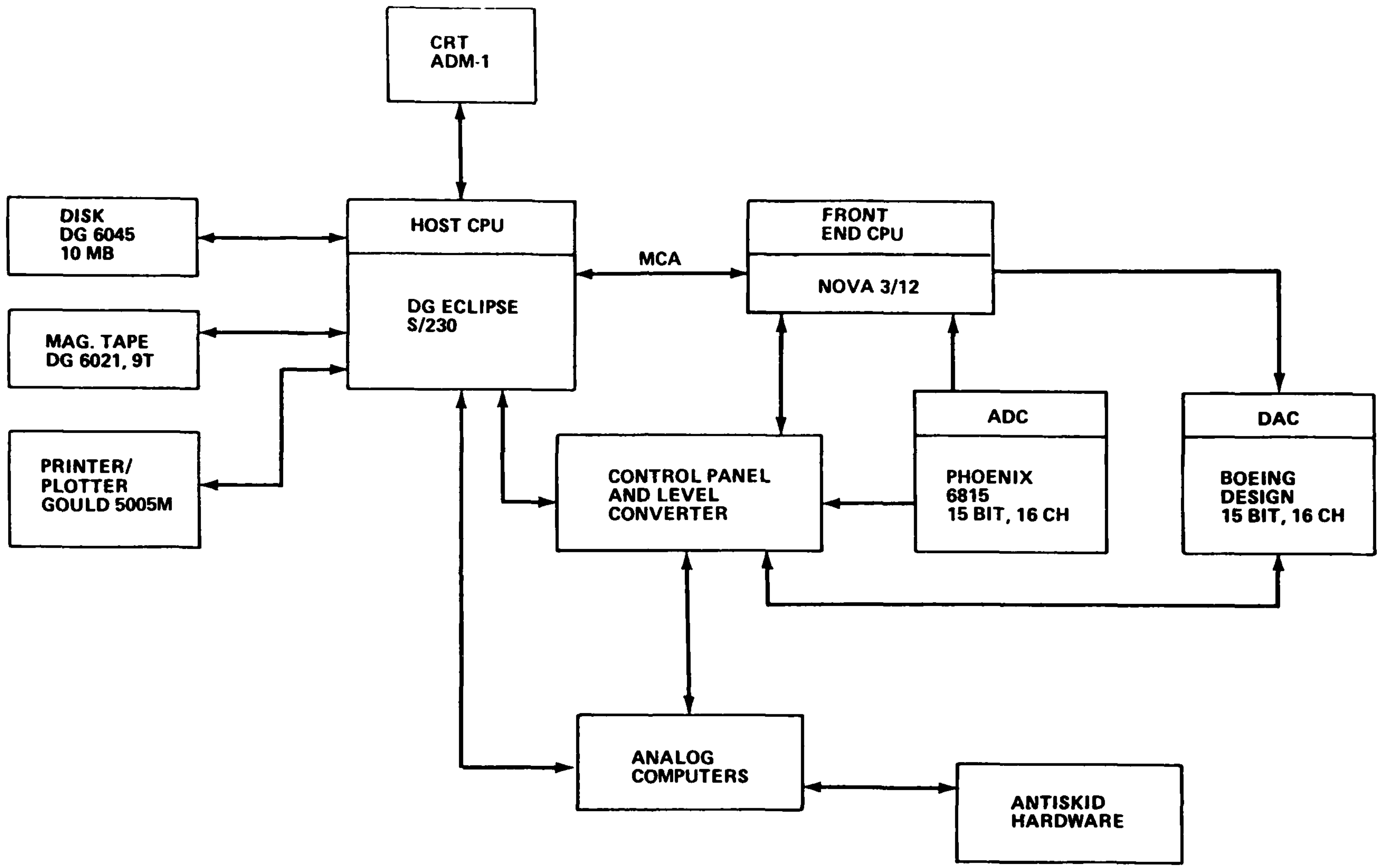


Figure C.2. Antiskid Lab Minicomputer System

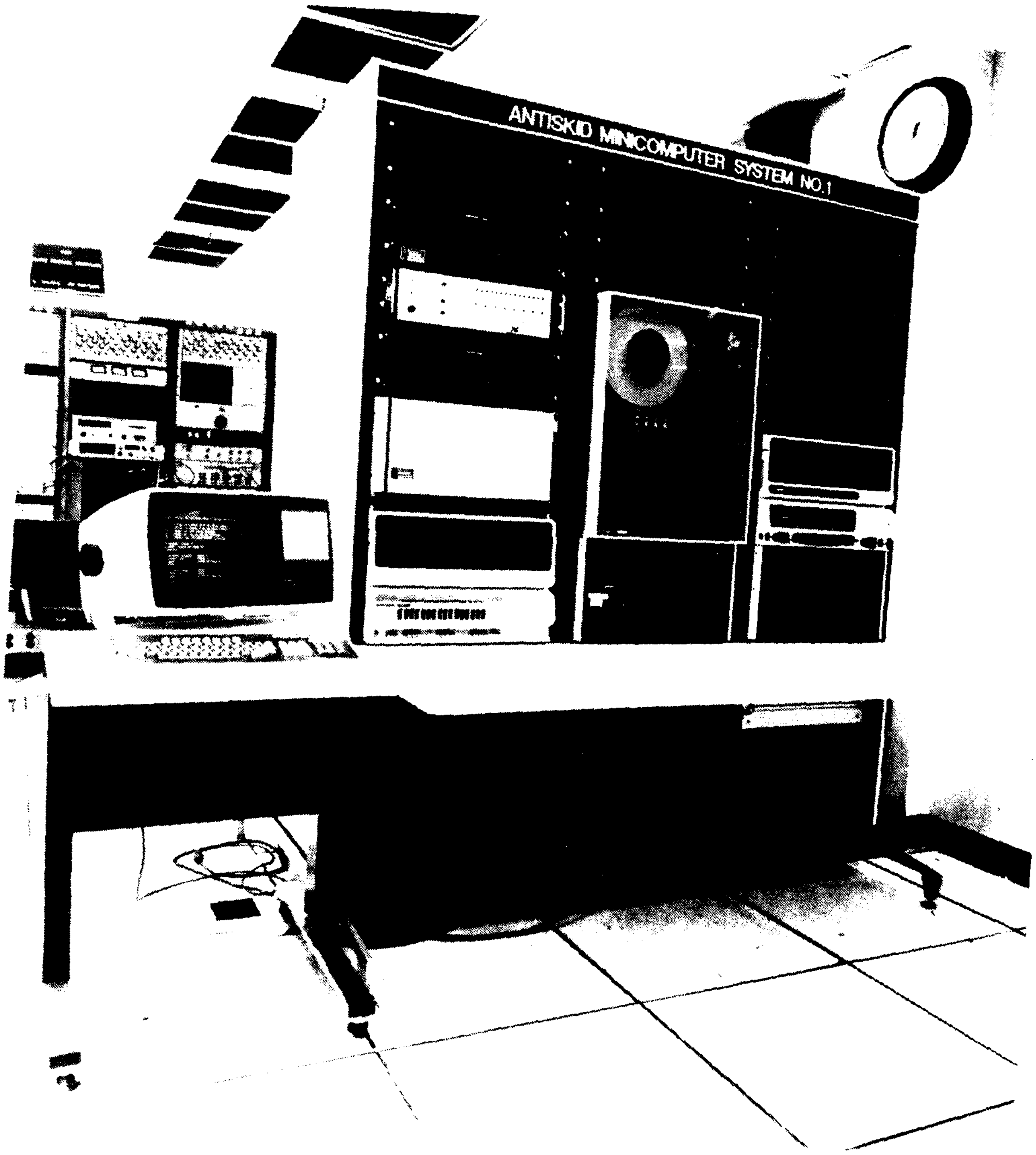


Figure C.3. Digital Minicomputer System, Hybrid Brake Control Laboratory

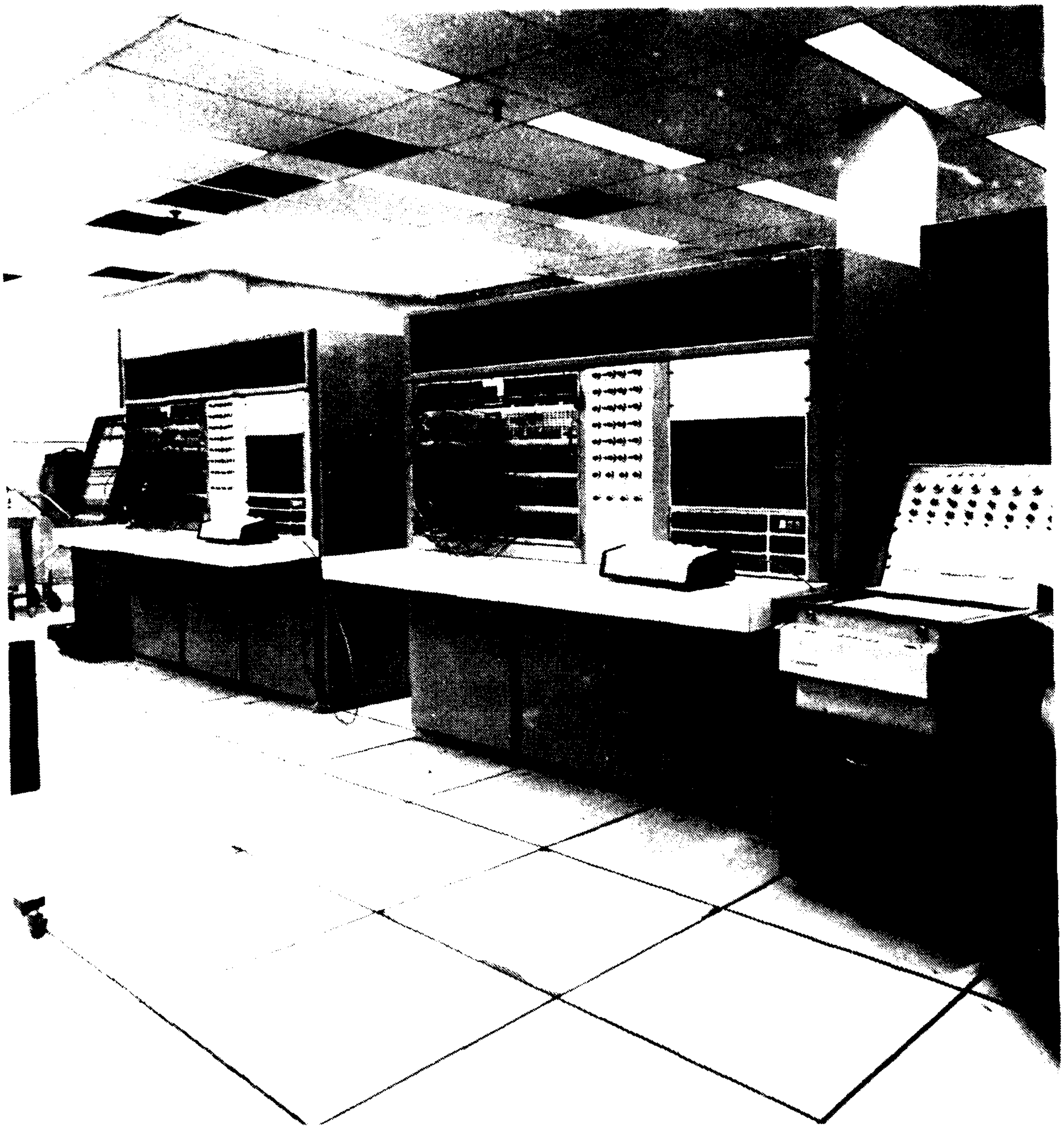


Figure C.4. Analog Computers, Hybrid Brake Control Laboratory

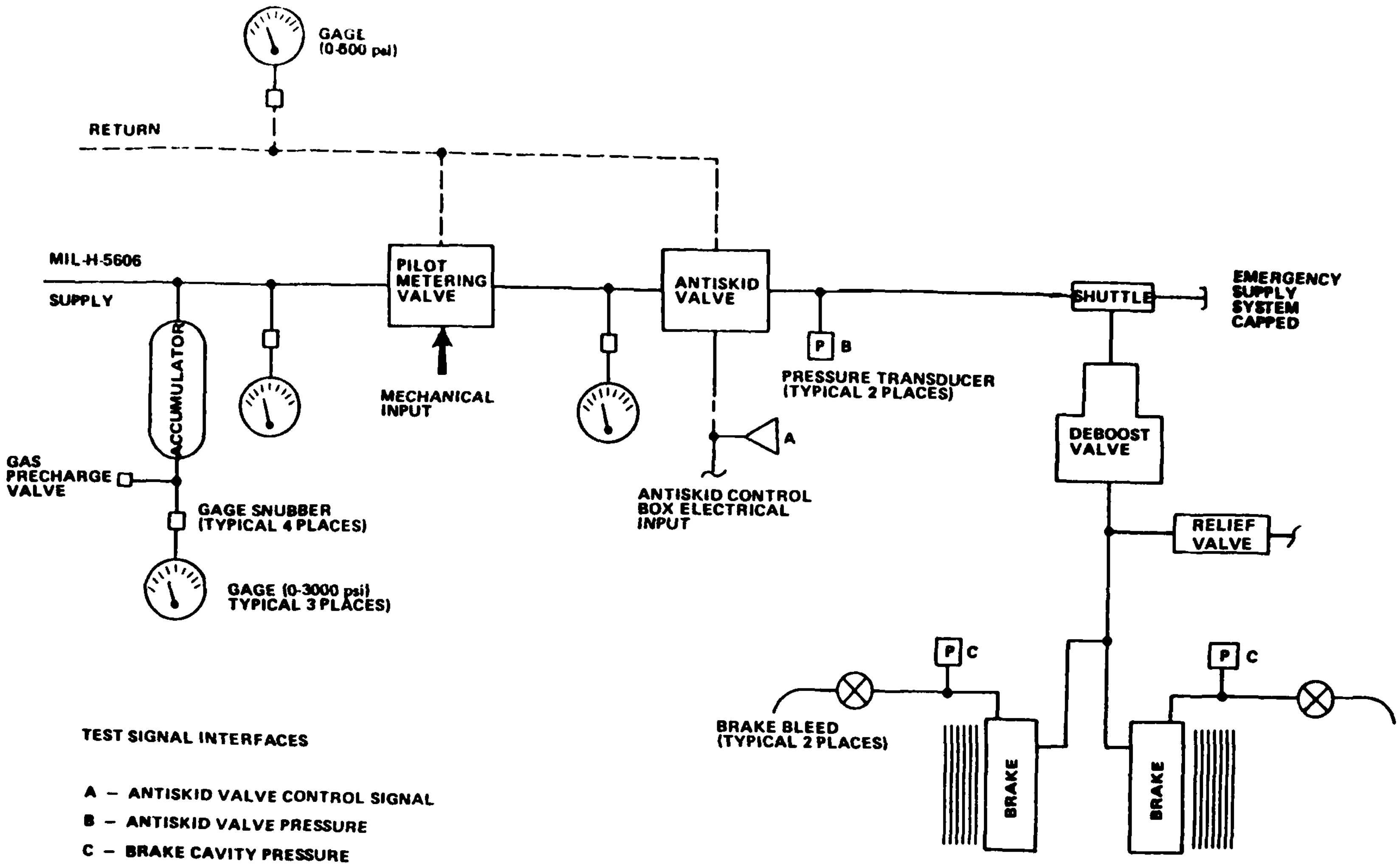


Figure C.5. **Test Setup – KC-135 Hydraulic Brake System Mockup for Baseline Tests**

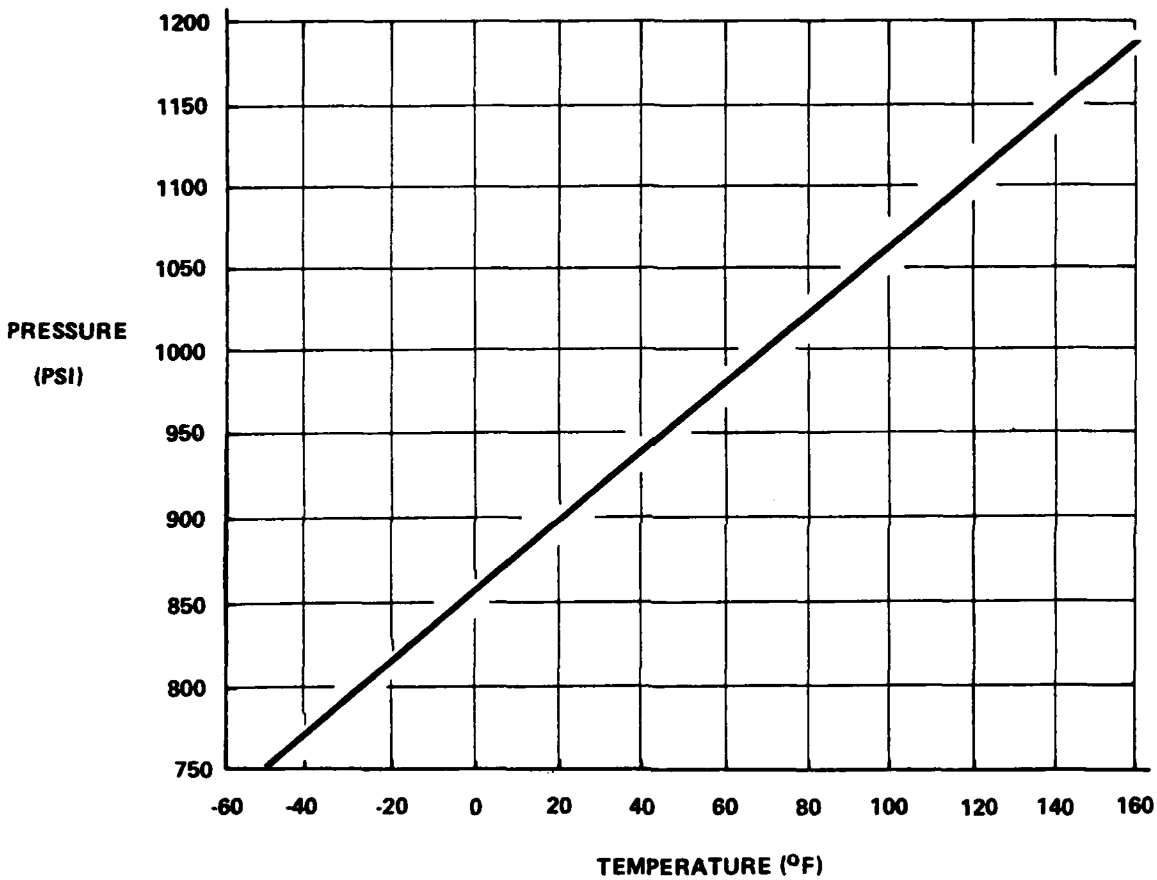


Figure C.6. Brake Accumlator Charging Curve

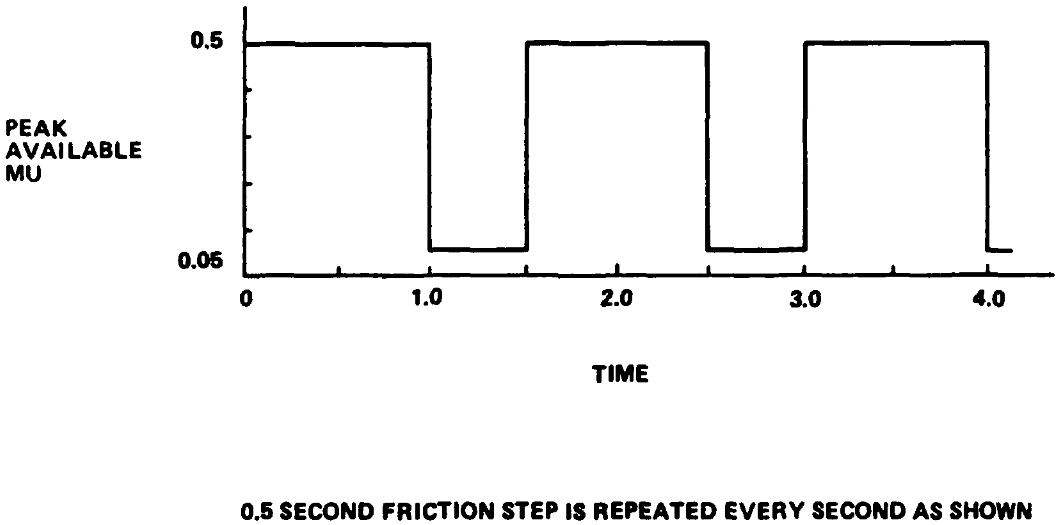


Figure C.7. Step Friction Test – Friction versus Time

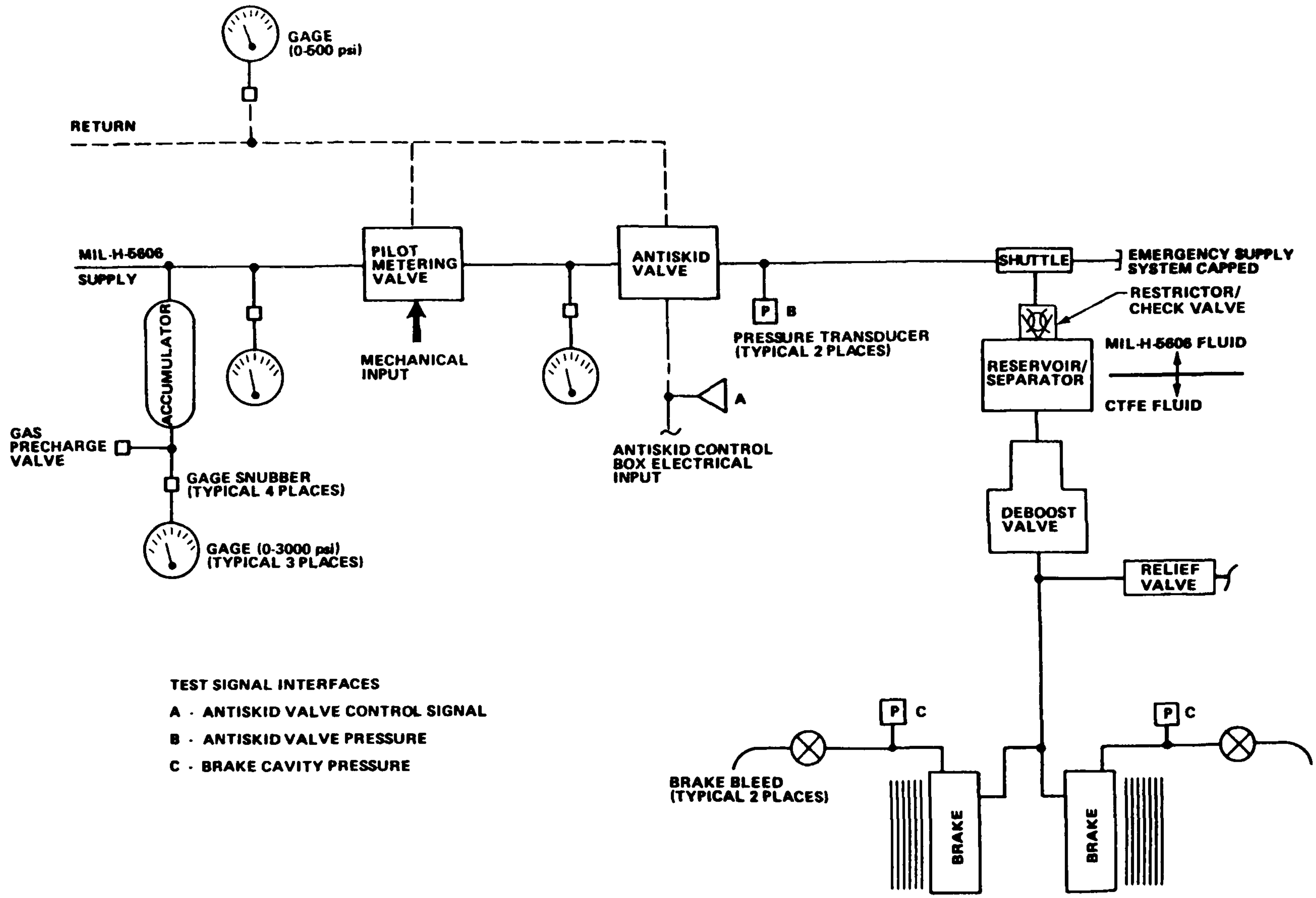


Figure C.8. Test Setup - Fireproof Hydraulic Brake System Mockup

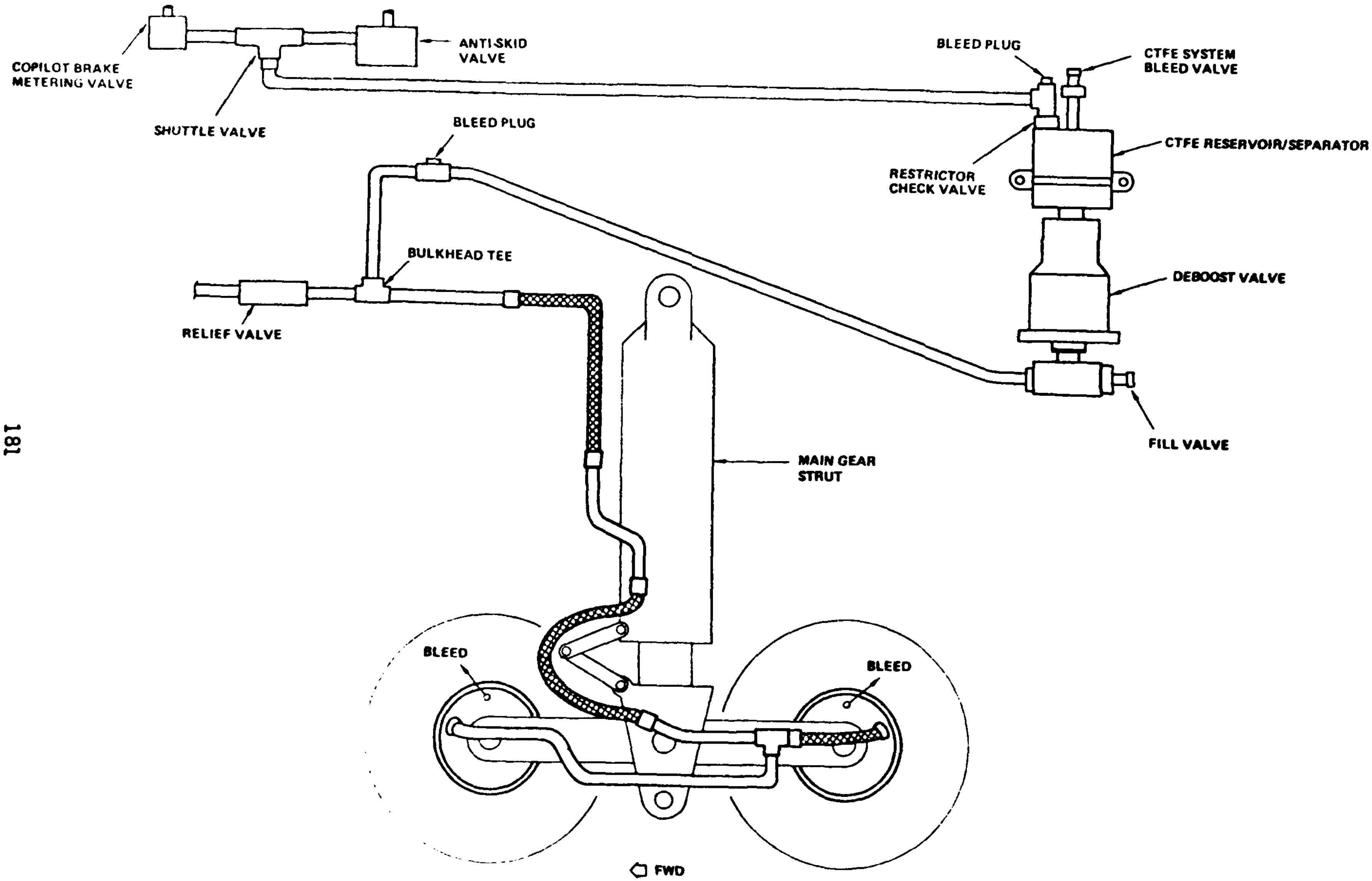


Figure C.9. FHBS Schematic

Table C.1 - Instrumentation Range, Accuracy and Resolution

ITEM	QTY	RANGE	ACCURACY	RESOLUTION	USE	COMMENT
Pressure Gage	3	0 - 3000 psi	5 psi	10 psi	Accumulator gas, Supply and Metering Valve	Indication Only
Pressure Gage	1	0 - 500 psi	5 psi	10 psi	Return Pressure	Indication Only
Pressure Tansducer	1	0 - 6000 psi	2 psi	1 psi	Antiskid Valve Output Pressure	
Pressure Transducer	1	0 - 3000 psi	2 psi	1 psi	Brake Pressure	
Thermocouple	1	-100 to 212 F	2 °F	1 °F	Environmental Temperature	
Environmental Chamber/ Temperature Capability	1	-100 to 212F	2 °F	--	Temperature Control	
MIL-H-5606 Fluid Regulated Pressure Supply Source	1	0 - 6600 psi	--	--	Fluid/Pressure Source	
Brush Chart Recorder (8 Channel)	1	--	--	--	Time History Data	

Table C.2 Frequence Response Test Conditions

Nominal Brake Pressure psi	Sinusiodal Pressure Fluctuation psi	Frequency Response Analyzer Inputs (Figures C.5 & C.8)
325	±100	A to B
650	±200	A to C
		B to C

Table C.3 Step Response Test Conditions

Initial Brake Pressure % of max	Final Brake Pressure % of max	Strip Chart Recorder Inputs (Figures C.5 & C.8)
0	50	A, B & C
0	80	
0	100	
20	50	
20	80	
20	100	
50	80	
50	100	
50	0	
80	0	
100	0	
50	20	
80	20	
100	20	
80	50	
100	50	

APPENDIX D

SYSTEM FLIGHTWORTHINESS TEST RESULTS

This appendix includes typical examples of the test data recorded during the system-level performance testing described in Section VI.2.d and Appendix B. Figures D.1 thru D.13 show the frequency response of the as-built C/KC-135 brake system. Typical constant friction stopping performance data are shown in Figures D.14 thru D.31. Step response data for both the as-built and two-fluid FHBS are shown in Figures D.32 thru D.79. Figures D.80 thru D.92 show the frequency response of the two-fluid brake system. Typical constant friction stopping performance data for the FHBS are shown in Figures D.93 thru D.110.

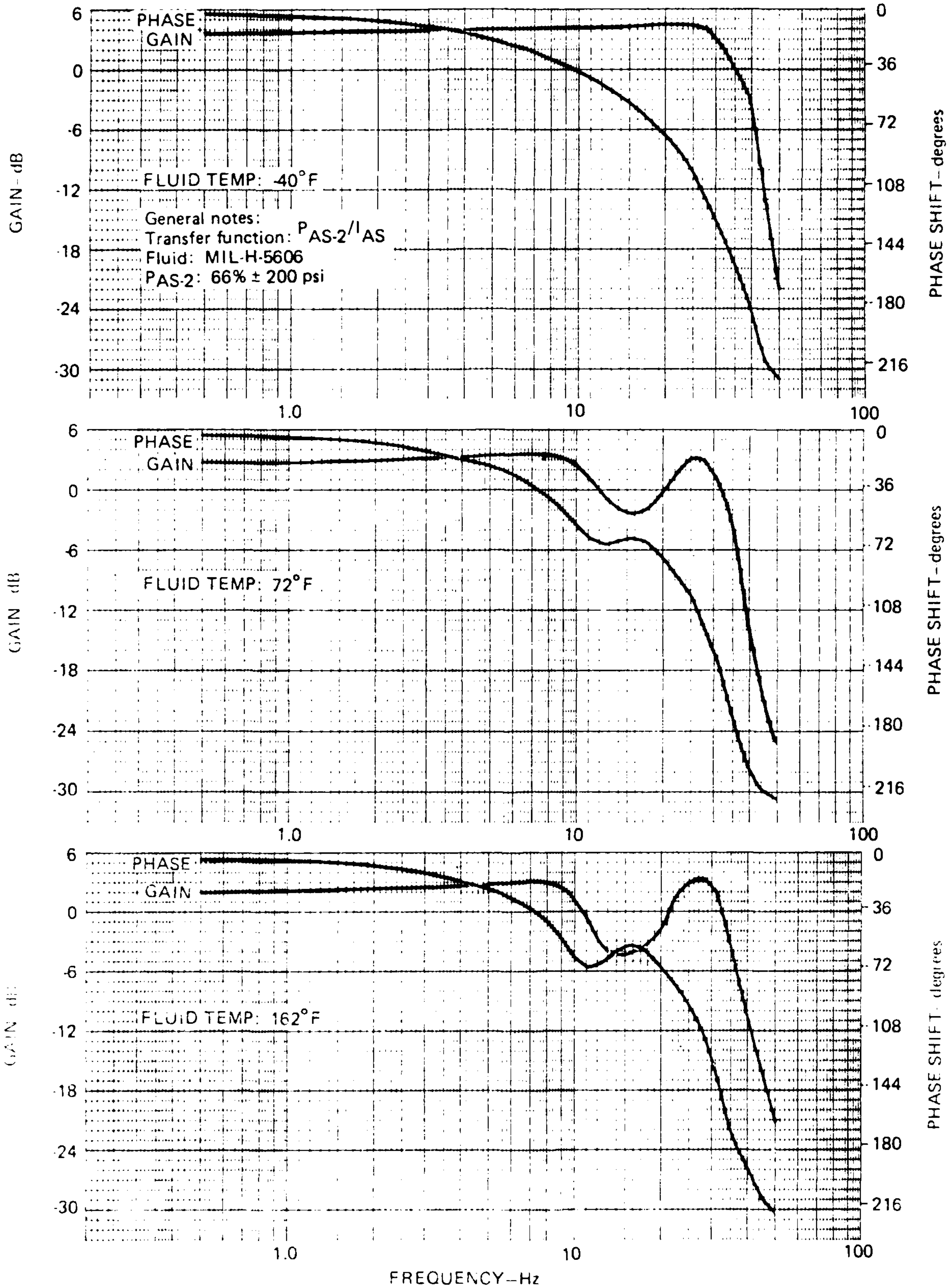


Figure D.1. As-Built System Antiskid Valve Performance Variation with Temperature

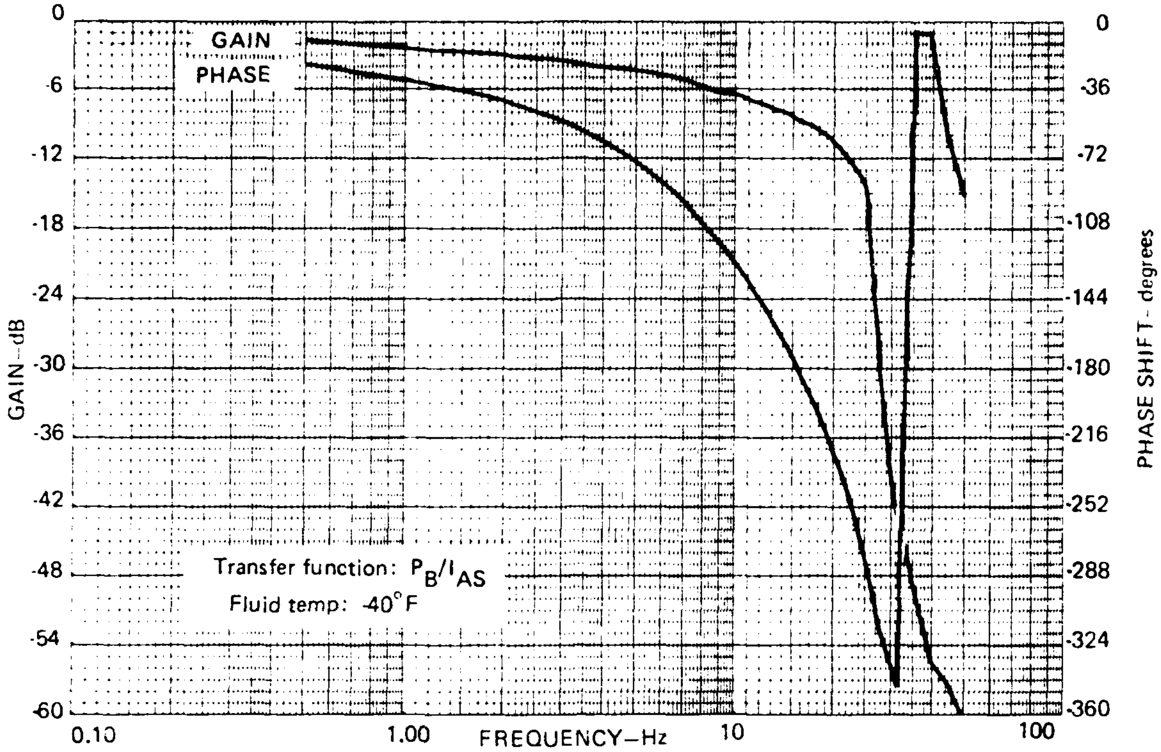


Figure D.4. As-built Brake System Frequency Response at -40° F, 33% ± 100 psi

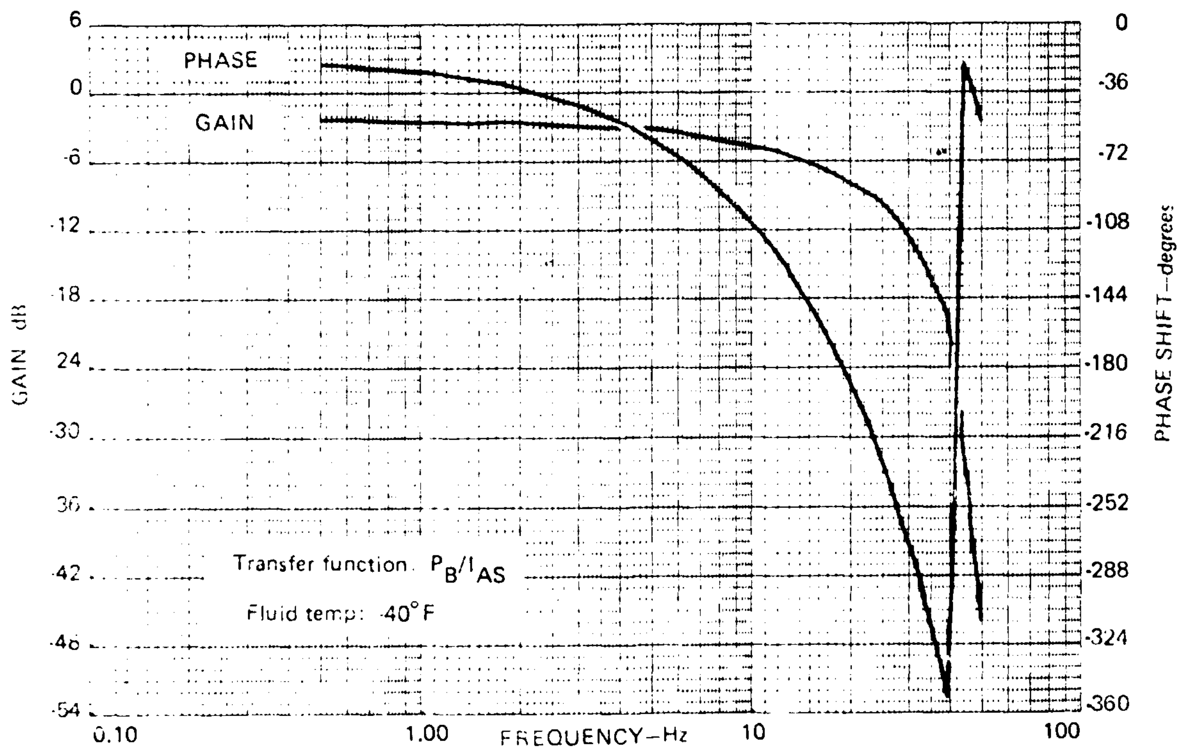


Figure D.5. As-built Brake System Frequency Response at -40° F, 66% ± 200 psi

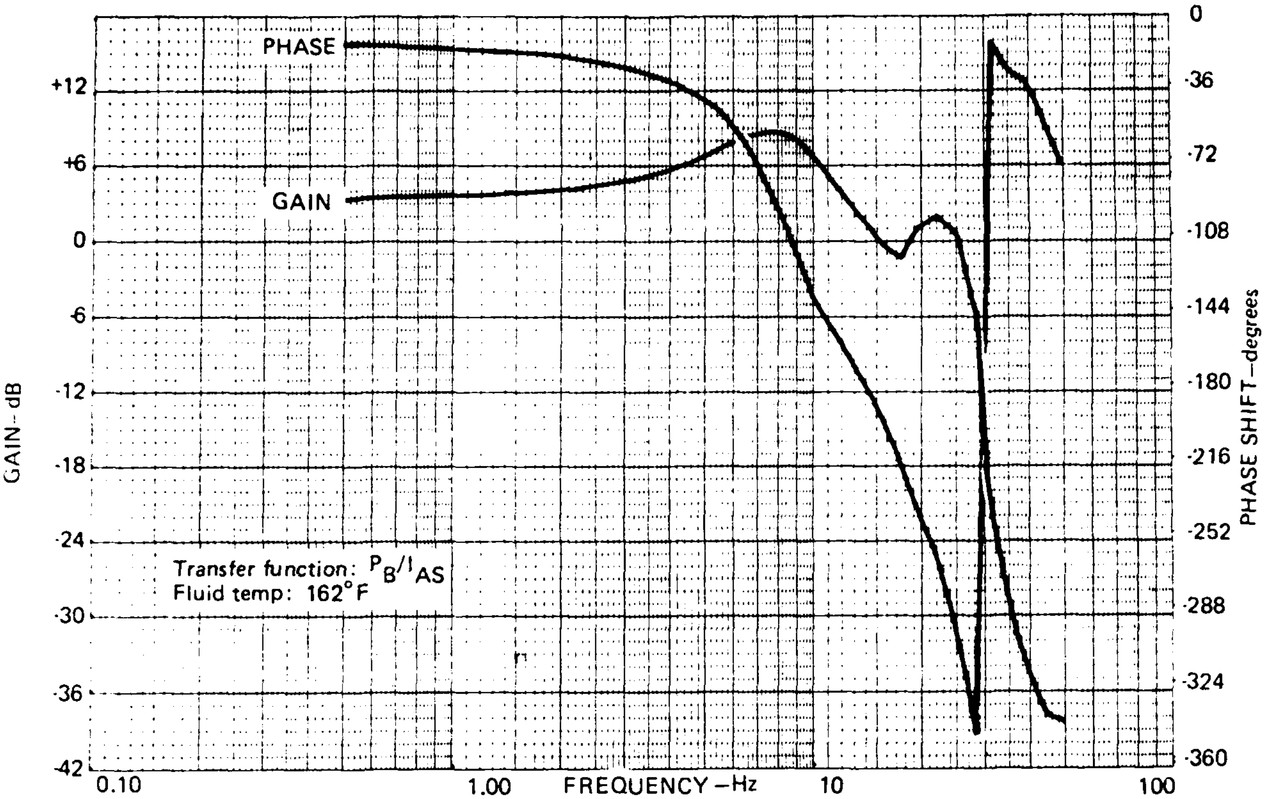


Figure D.6. As-Built Brake System Frequency Response at 160° F, 33% ± 100 psi

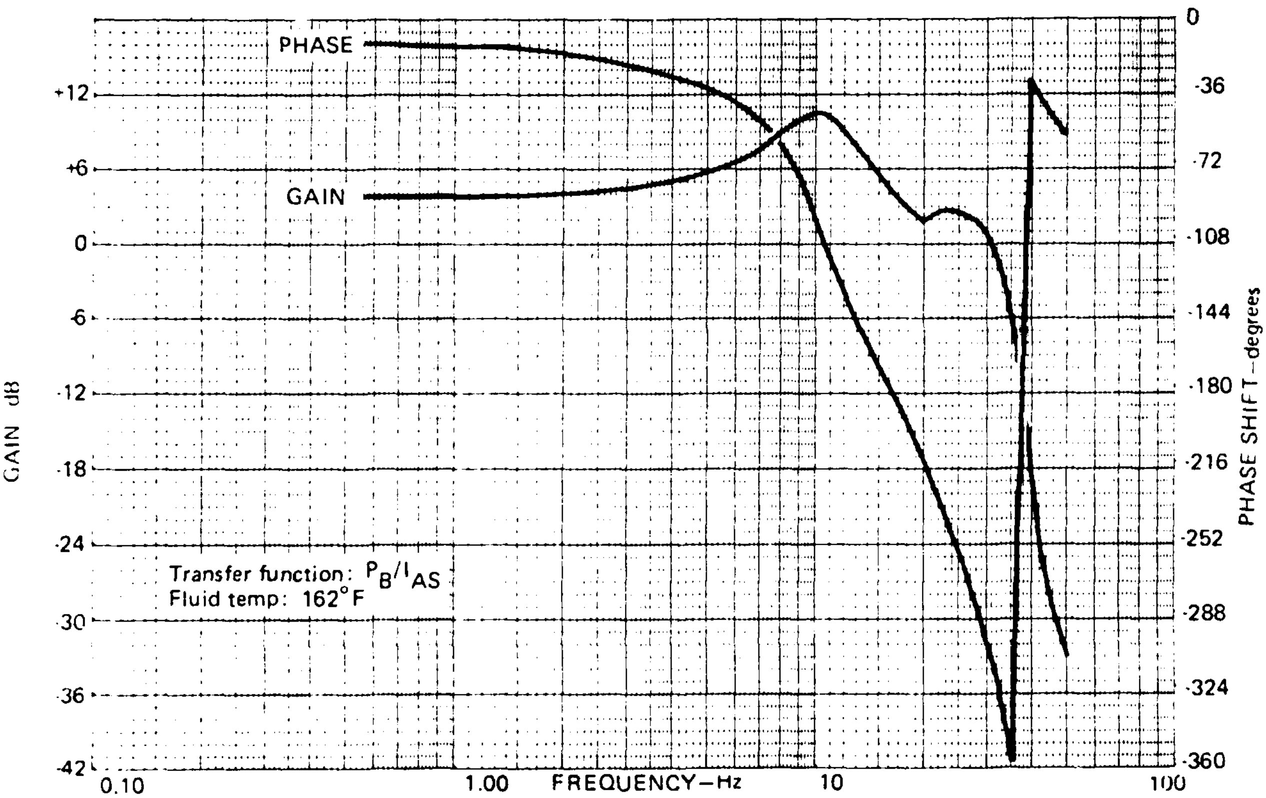


Figure D.7. As-Built Brake System Frequency Response at 160° F, 66% ± 200 psi

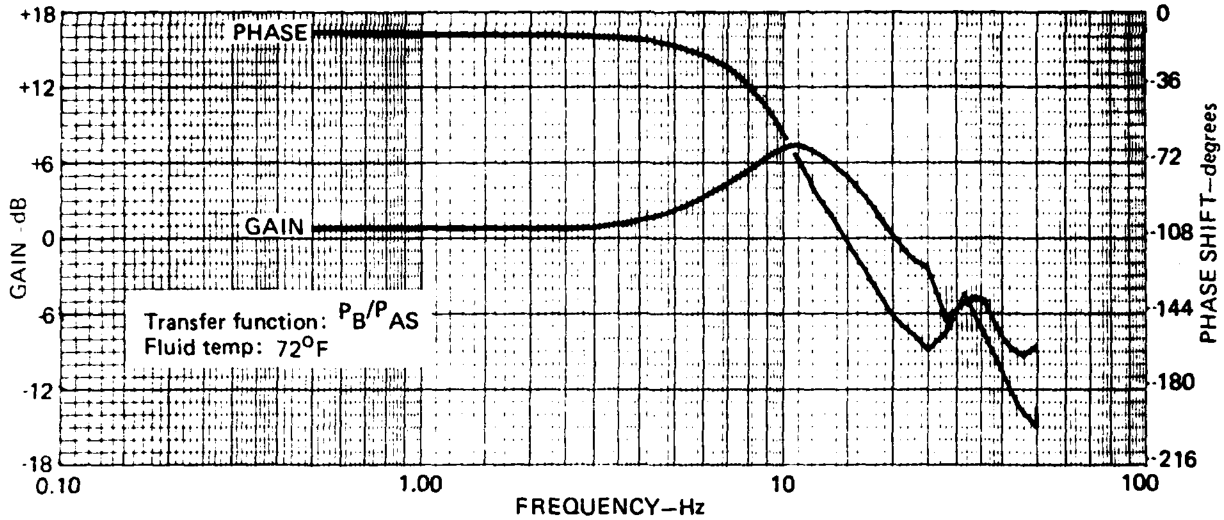


Figure D.8. As-Built Brake Hydraulic System Frequency Response at Room Temperature, 33% ± 100 psi

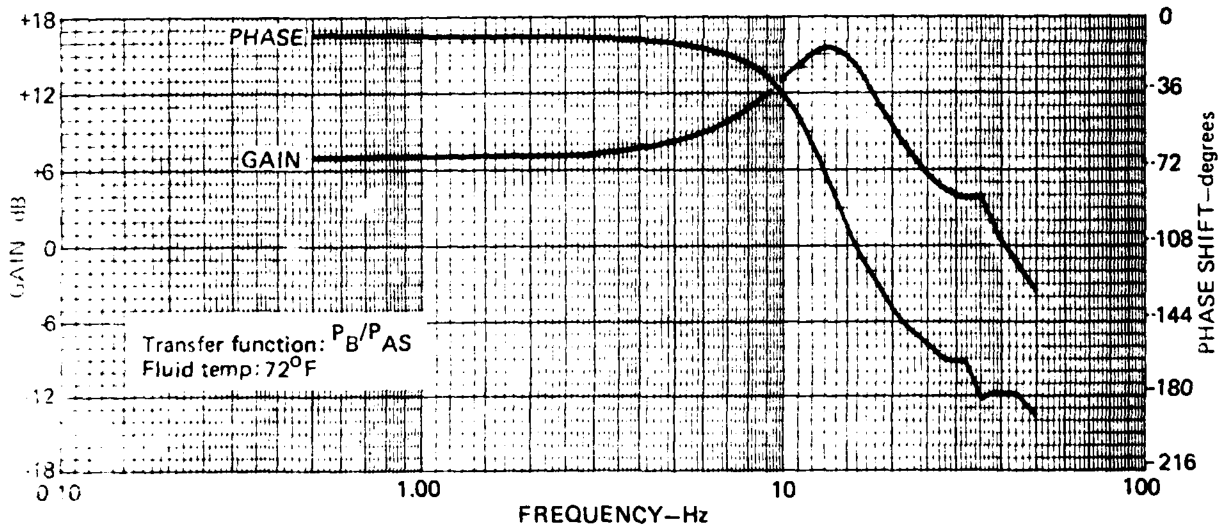


Figure D.9. As-Built Brake Hydraulic System Frequency Response at Room Temperature, 66% ± 200 psi

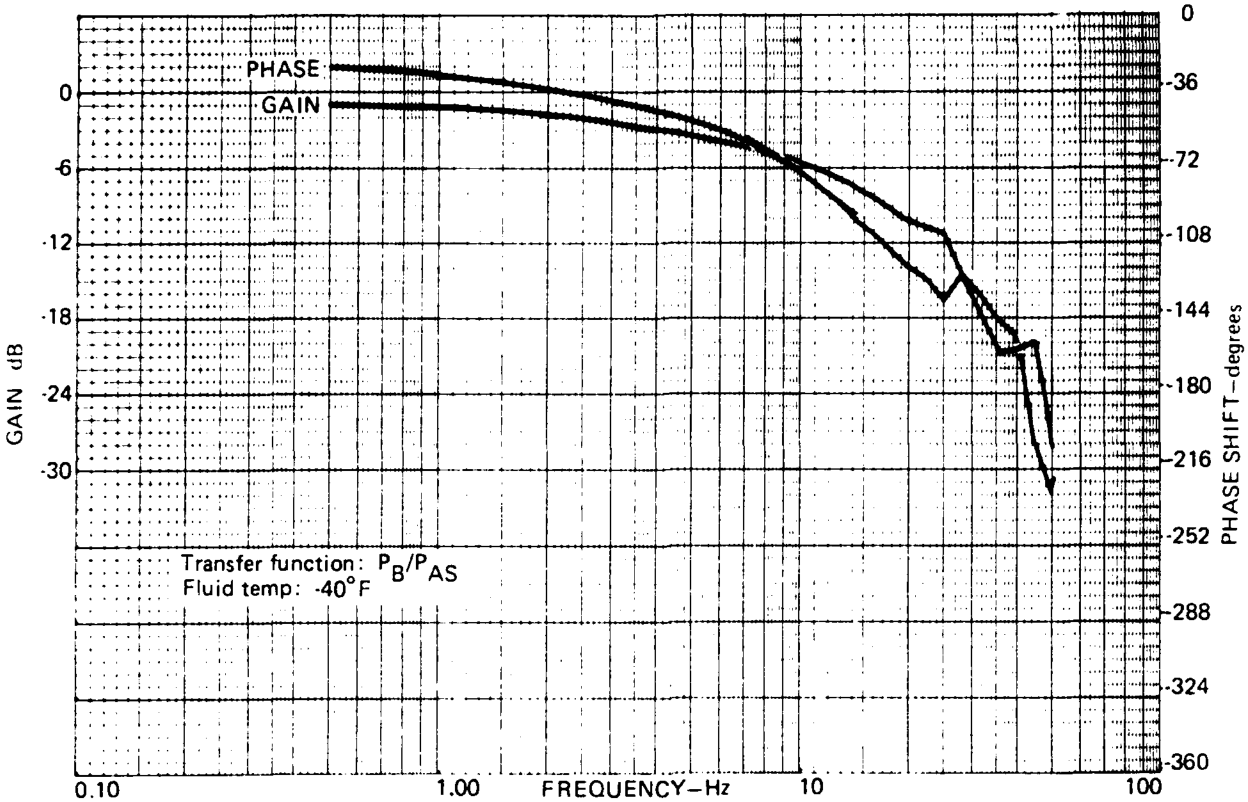


Figure D.10. As-Built Brake Hydraulic System Frequency Response at -40°F, 33% ± 100 psi

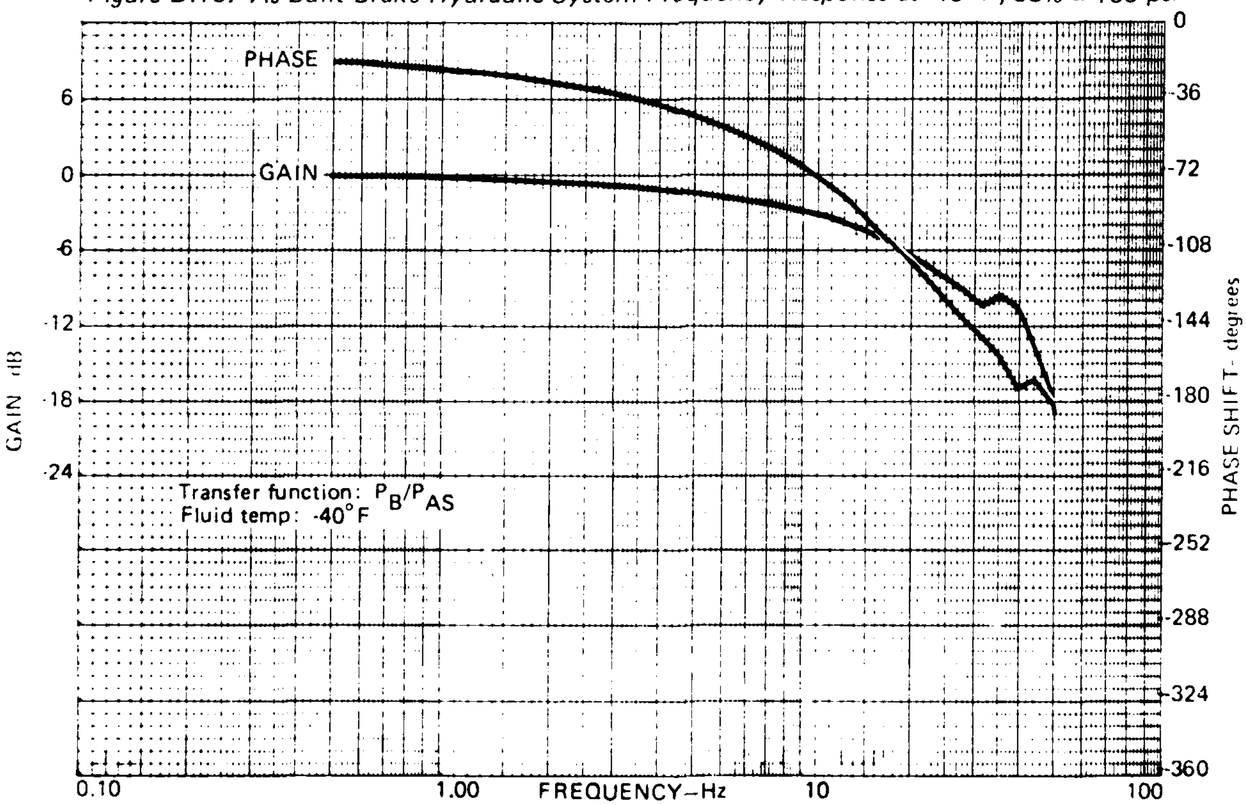


Figure D.11. As-Built Brake Hydraulic System Frequency Response at -40°F, 66% ± 200 psi

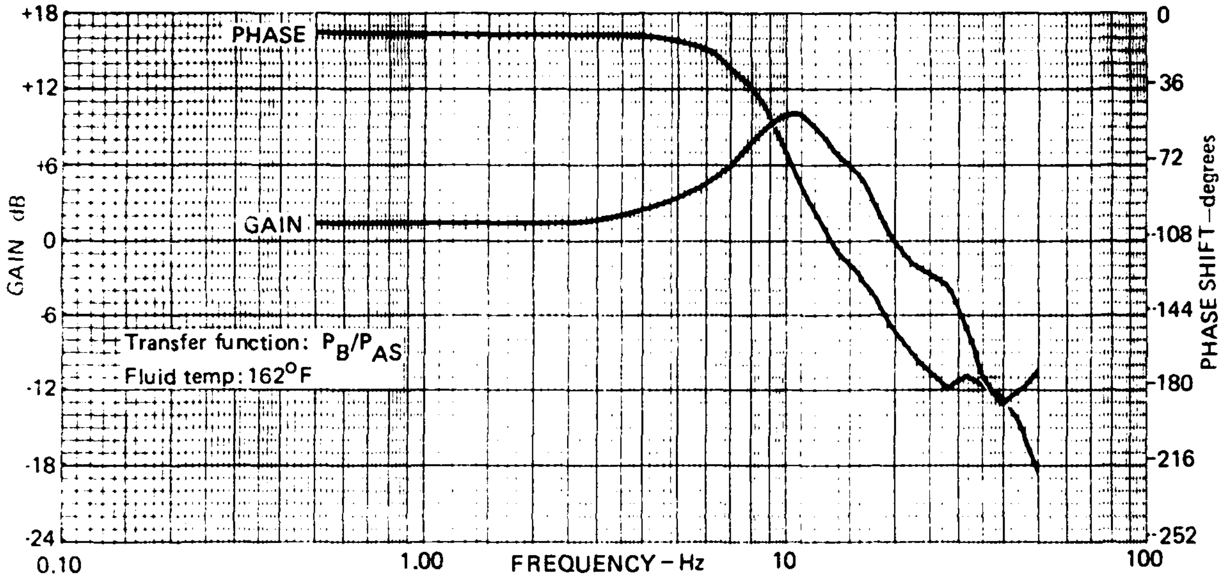


Figure D.12. As-Built Brake Hydraulic System Frequency Response at 160°F, 33% ± 100 psi

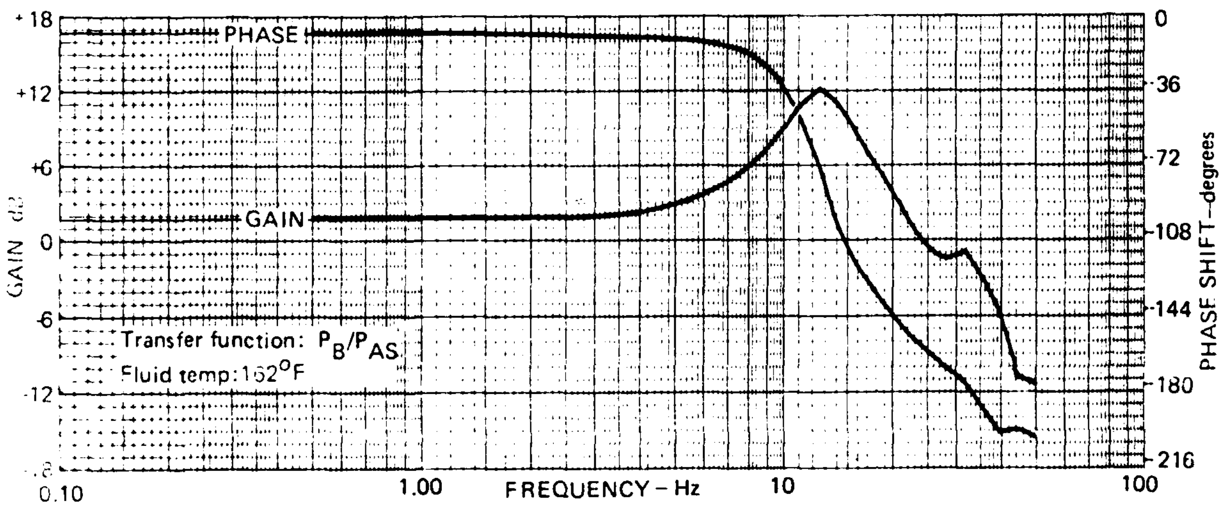


Figure D.13. As-Built Brake Hydraulic System Frequency Response at 160°F, 66% ± 200 psi

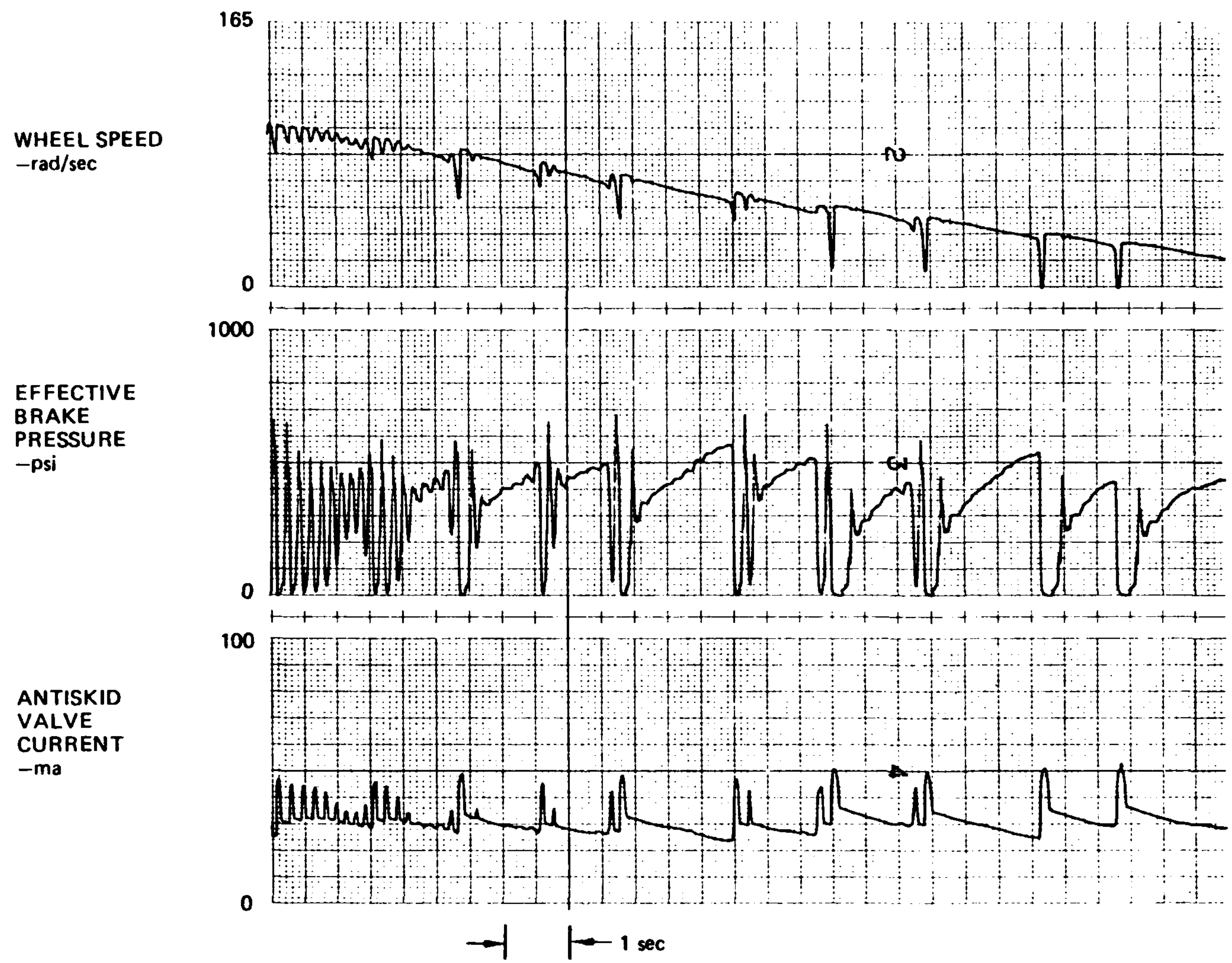


Figure D.14. As-Built Brake System Performance at Room Temperature, Mu = 0.6

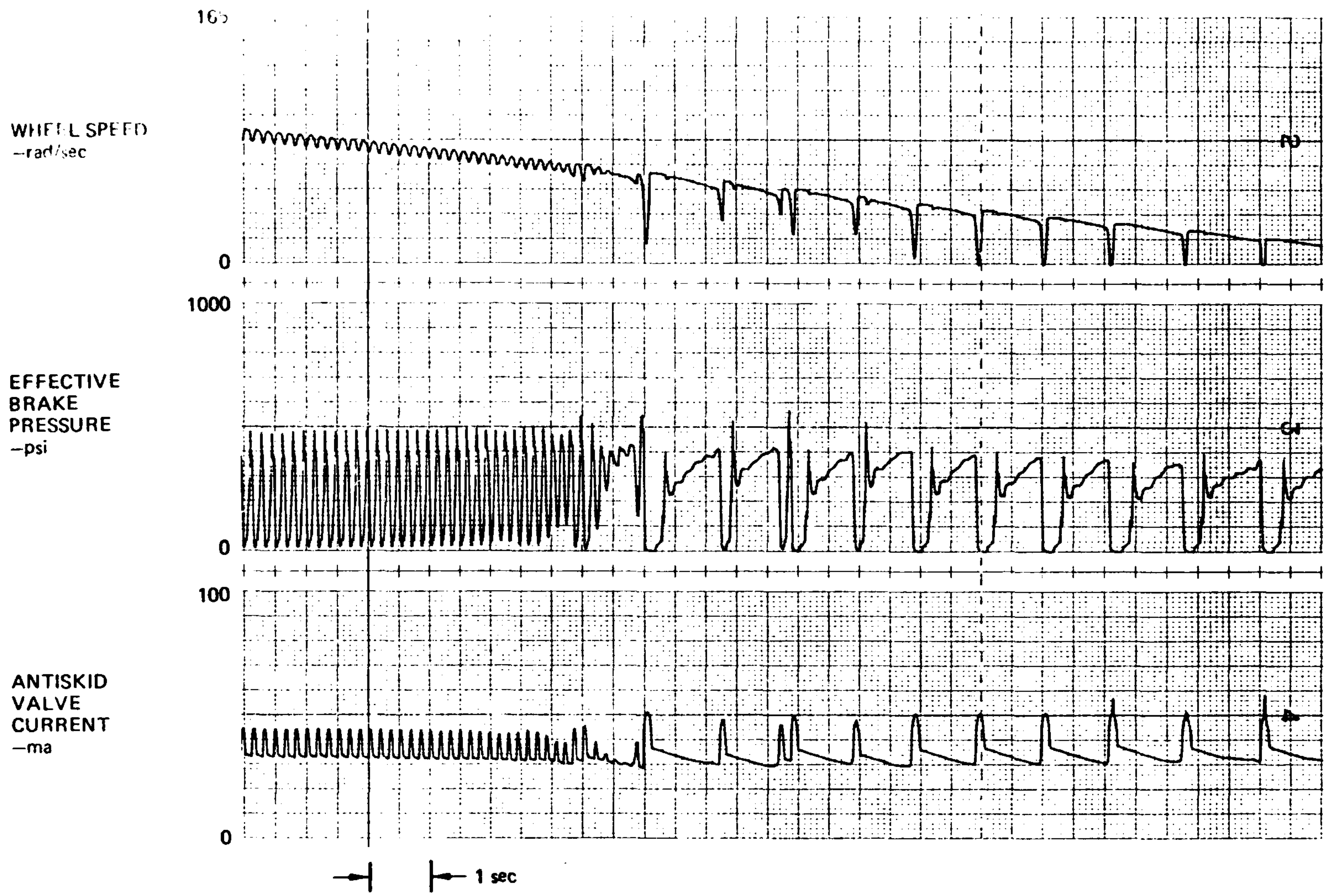


Figure D.15. As-Built Brake System Performance at Room Temperature, Mu = 0.5

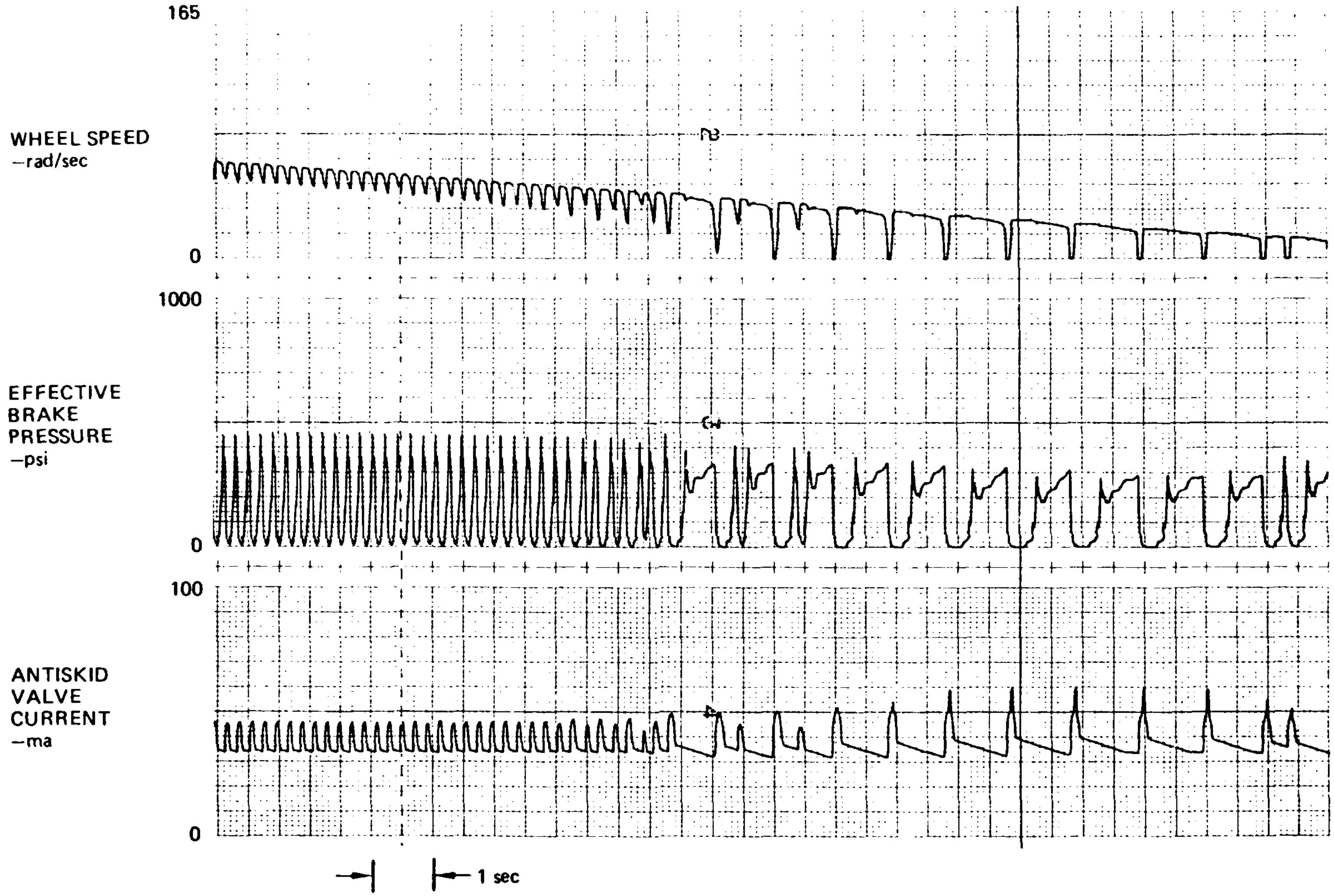


Figure D.16. As-Built Brake System Performance at Room Temperature, Mu = 0.4

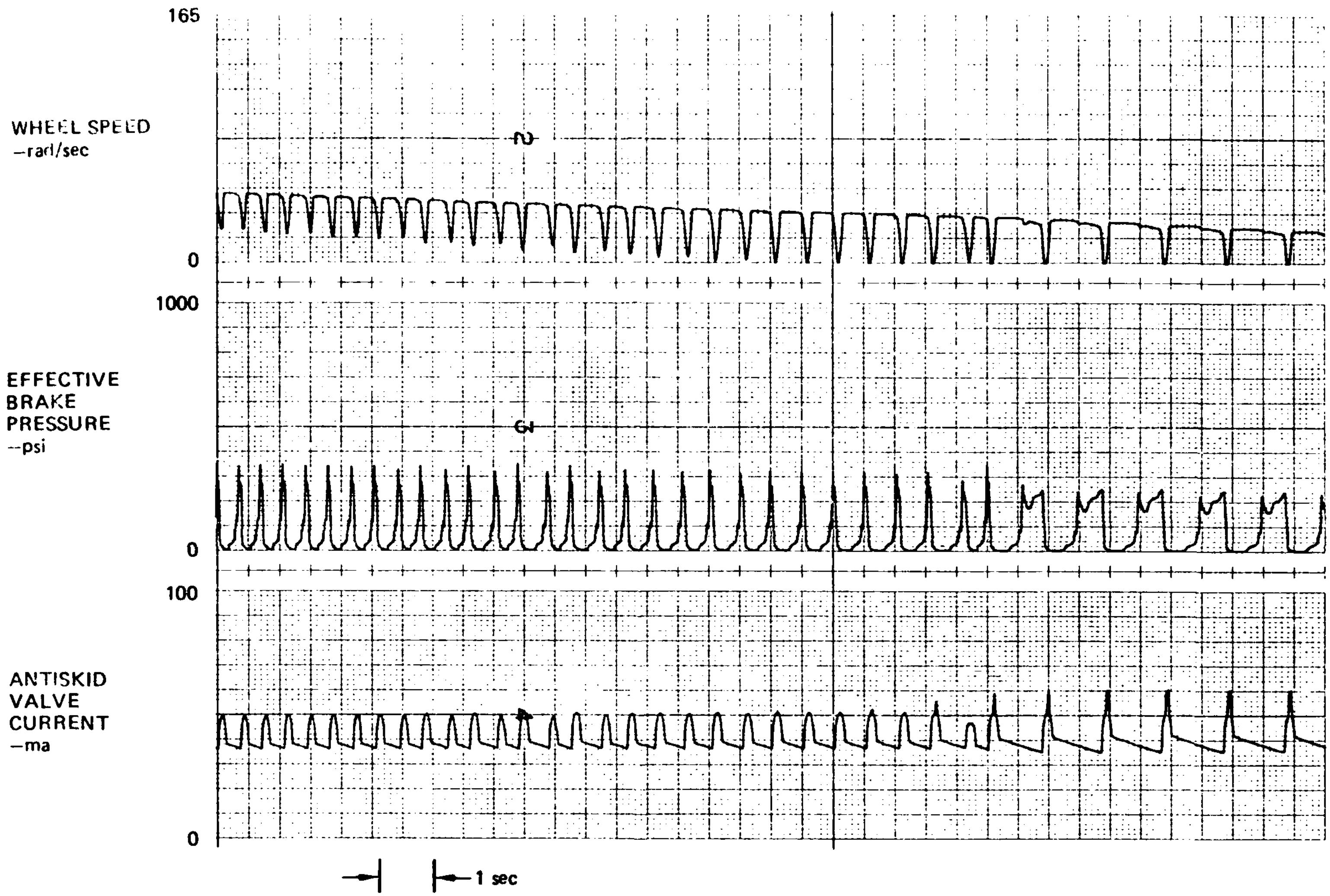


Figure D.17. As-Built Brake System Performance at Room Temperature, Mu = 0.3

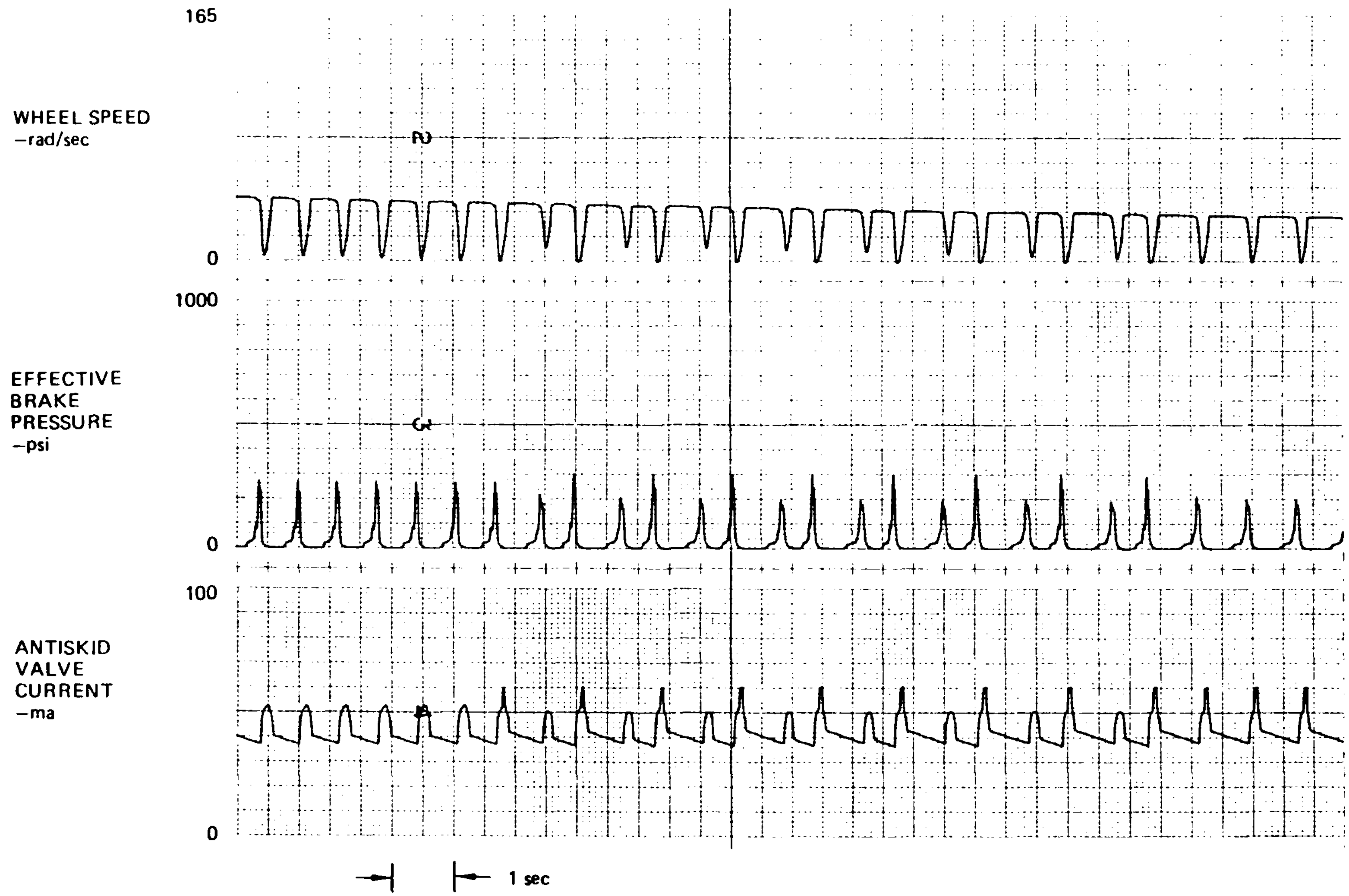


Figure D.18. As-Built Brake System Performance at Room Temperature, Mu =0.2

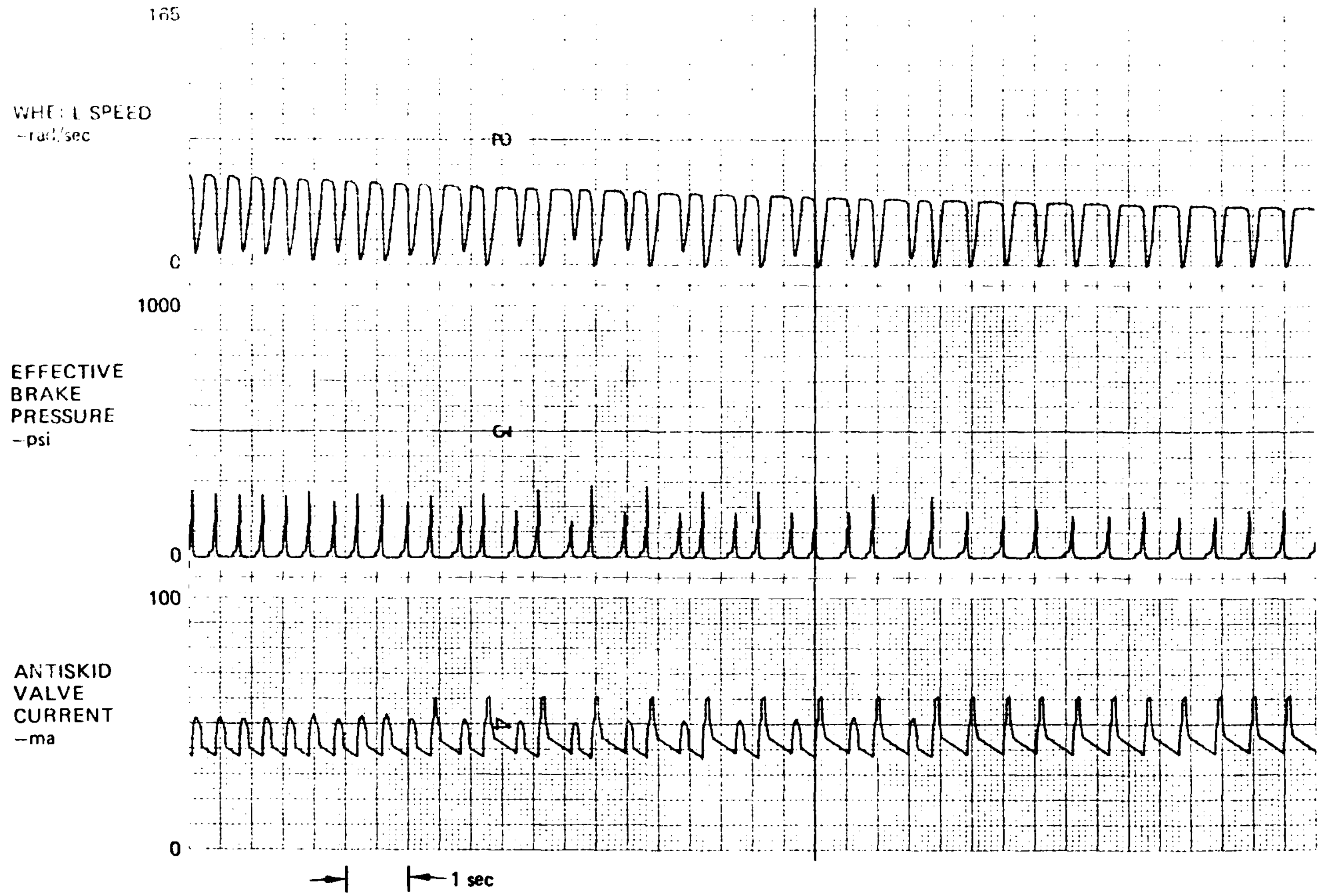


Figure D.19. As-Built Brake System Performance at Room Temperature, Mu = 0.1

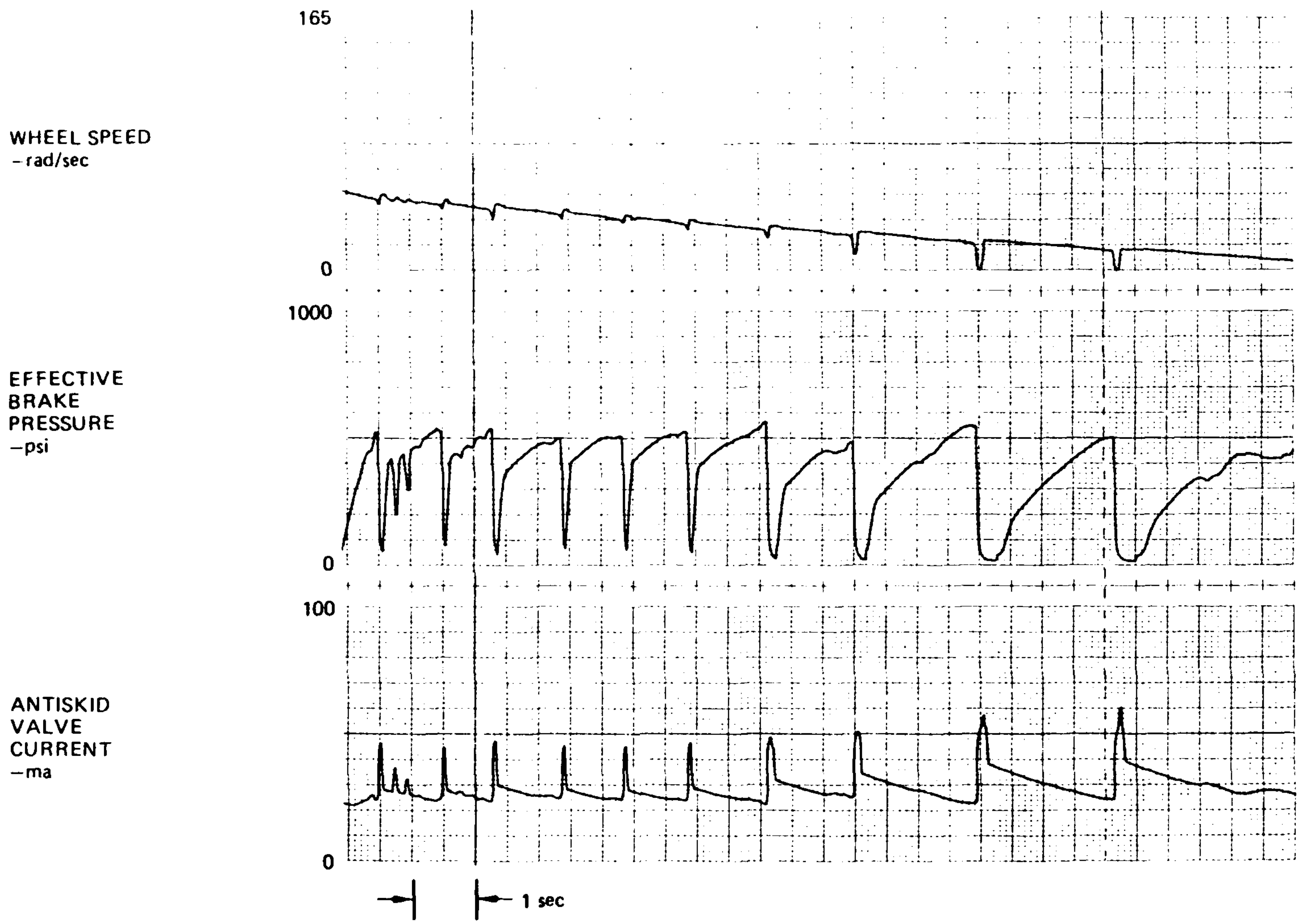


Figure D.20. As-Built Brake System Performance at -40°F, Mu =0.6

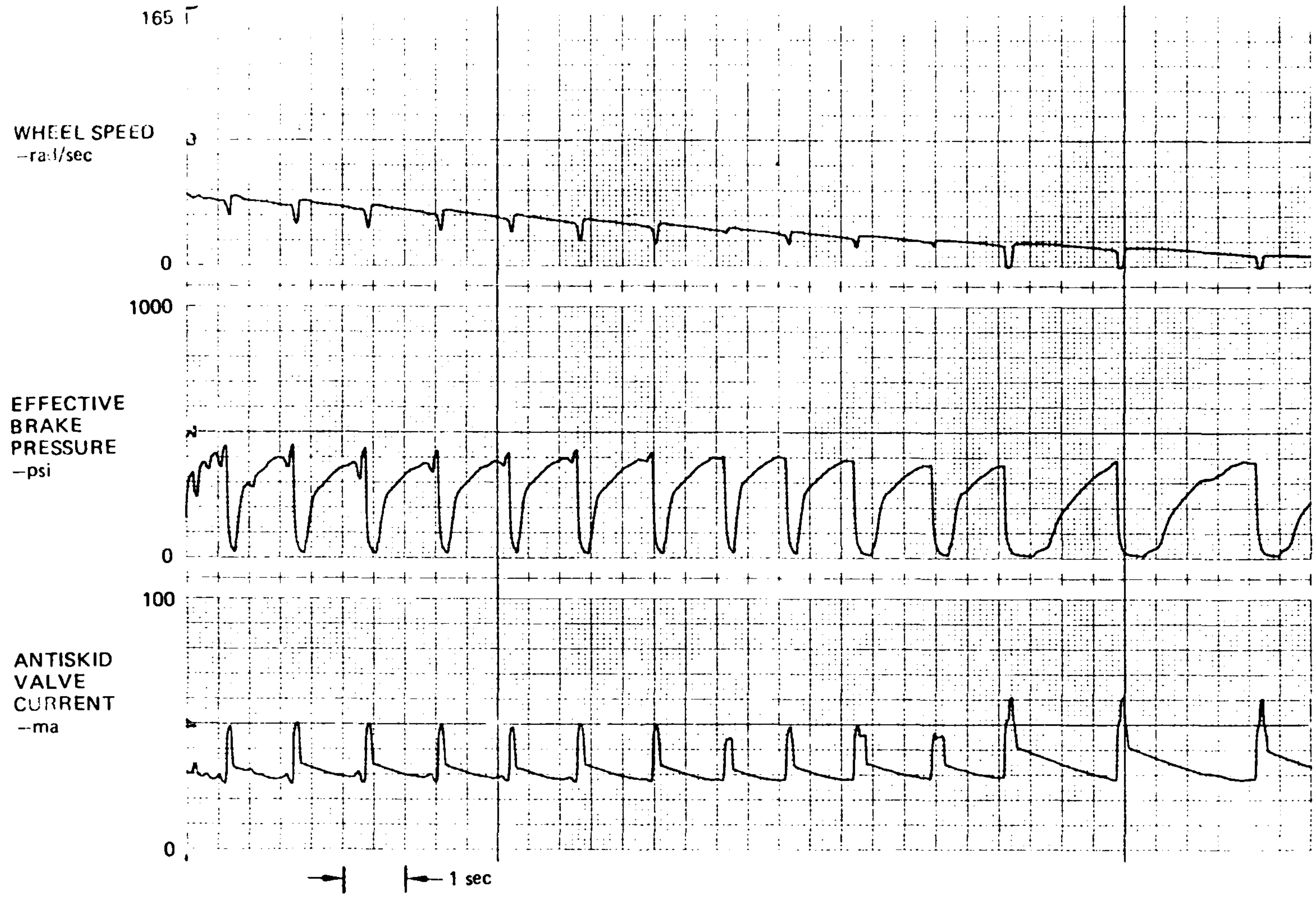


Figure D.21. As-Built Brake System Performance at -40 ^{O}F, Mu = 0.5

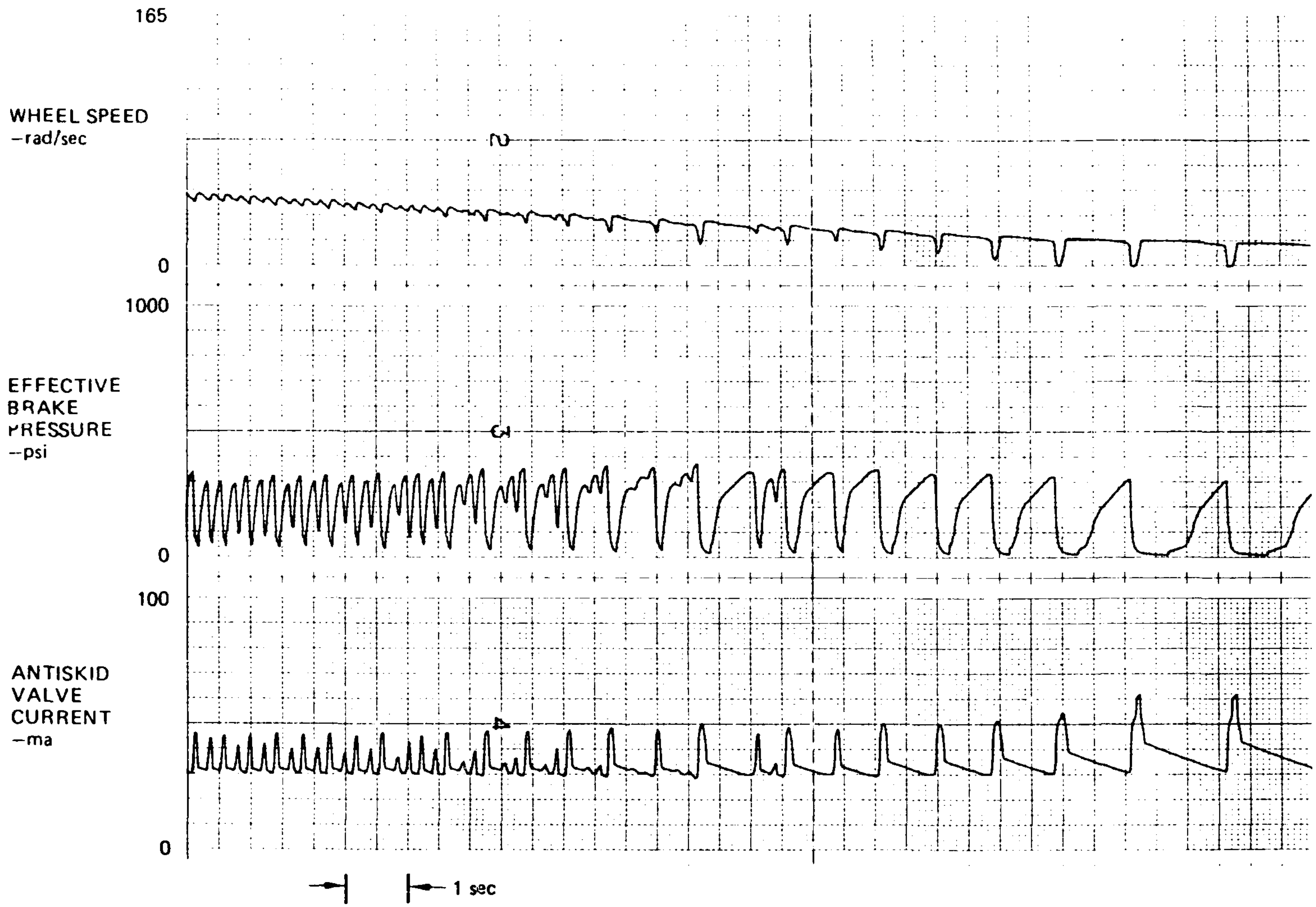


Figure D.22. As-Built Brake System Performance at -40^{O}F, Mu = 0.4

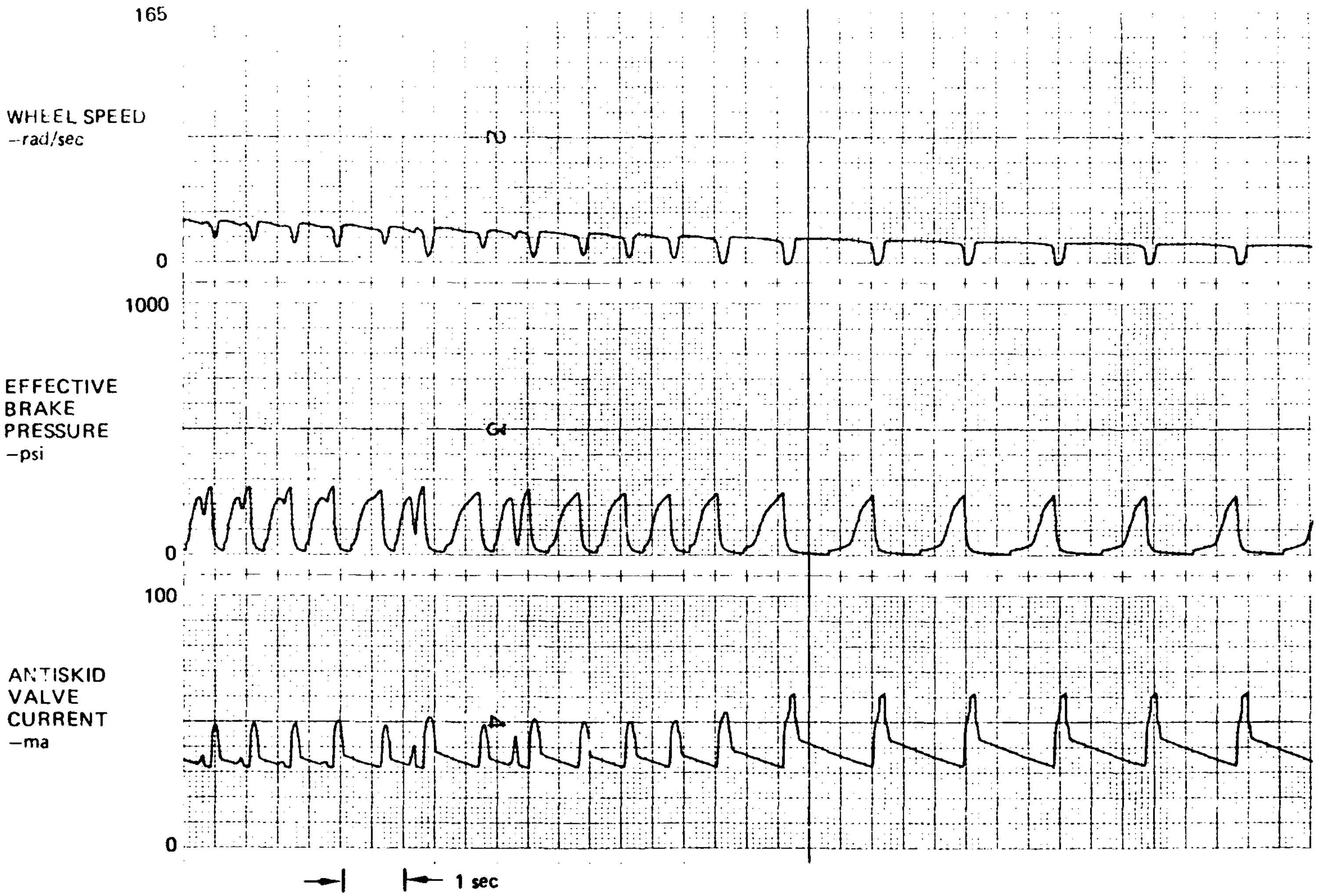


Figure D.23. As-Built Brake System Performance at -40^{O}F, Mu = 0.3

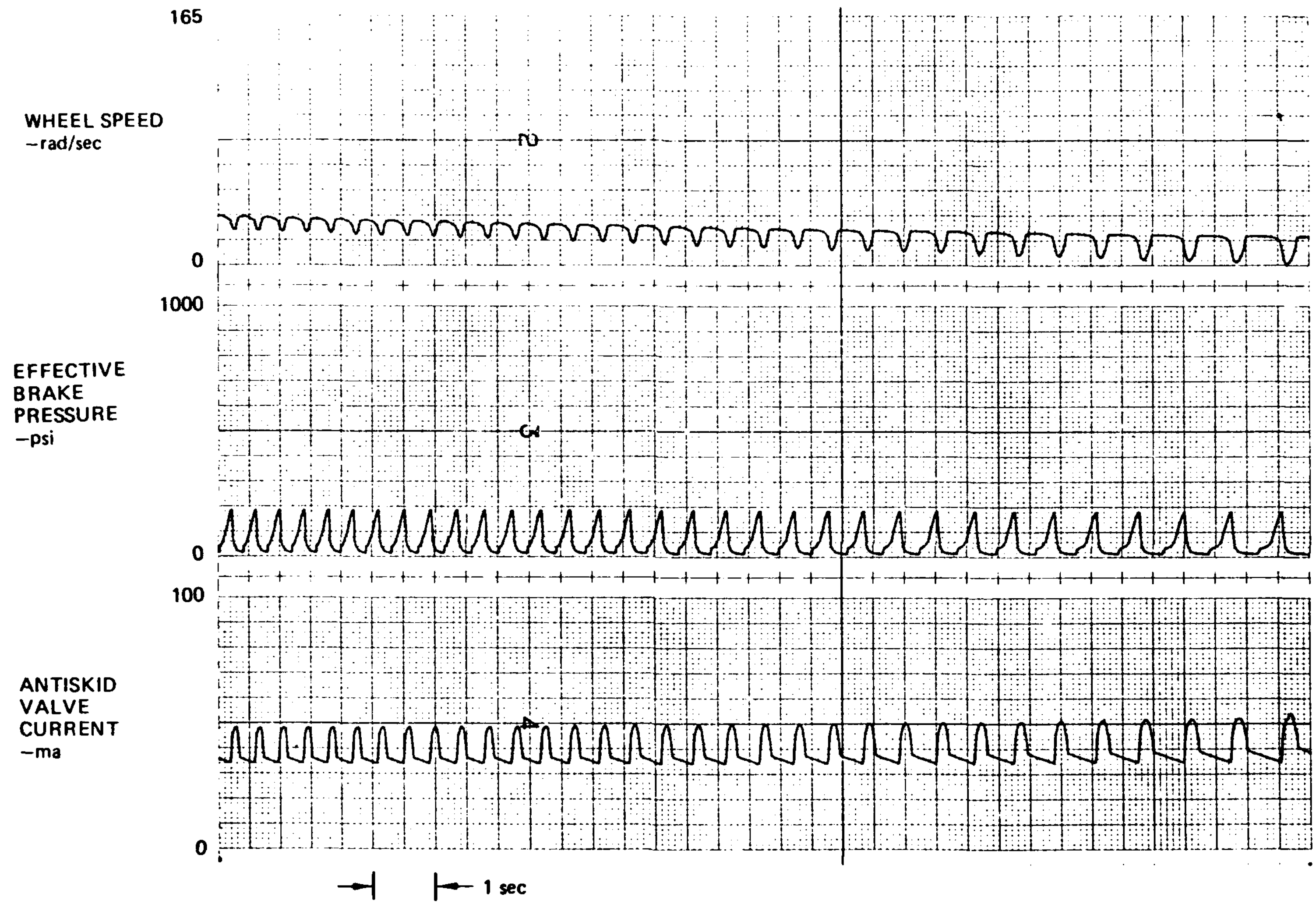


Figure D.24. As-Built Brake System Performance at -40°F, Mu = 0.2

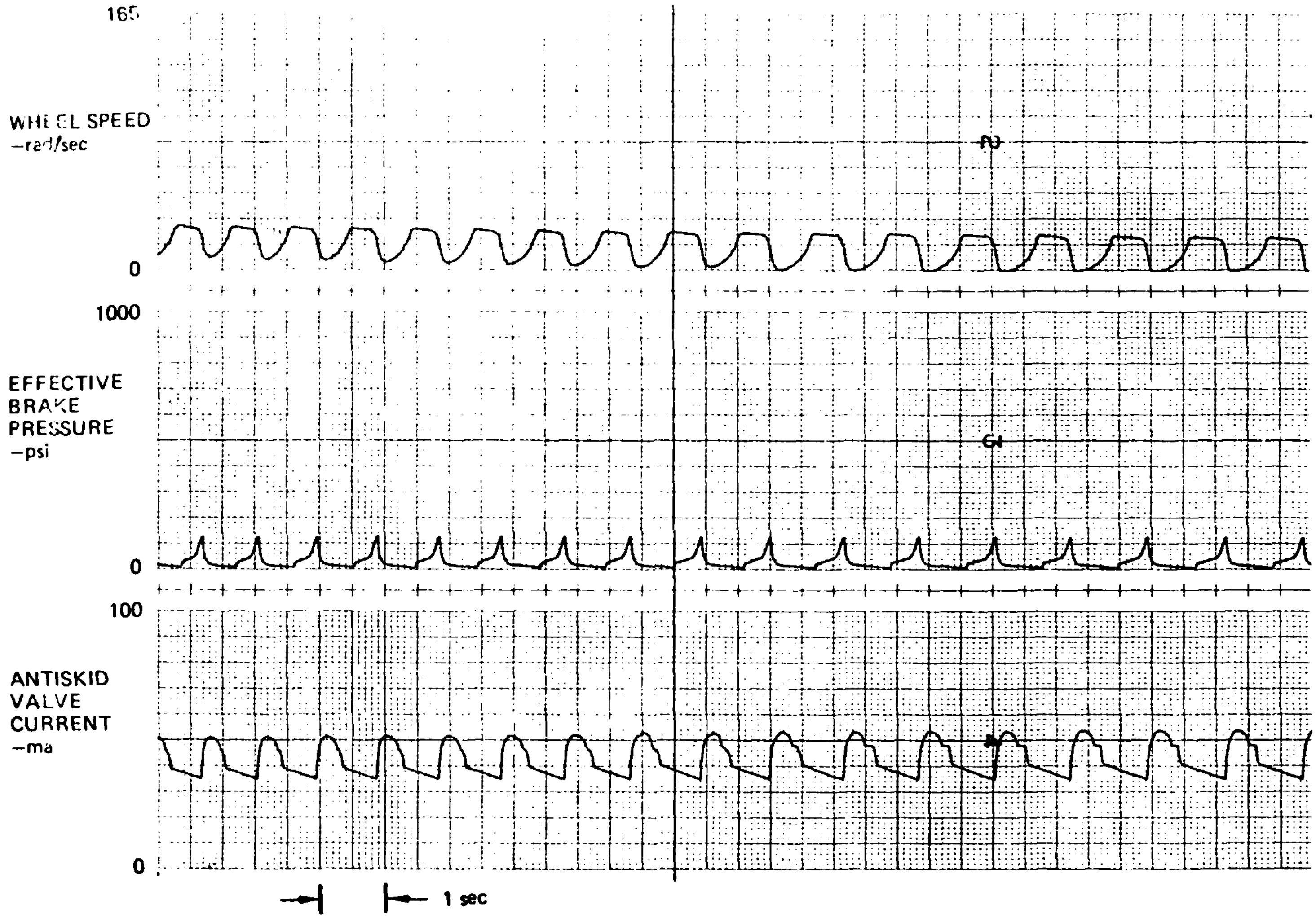


Figure D.25. As-Built Brake System Performance at -40^{o}F, Mu = 0.1

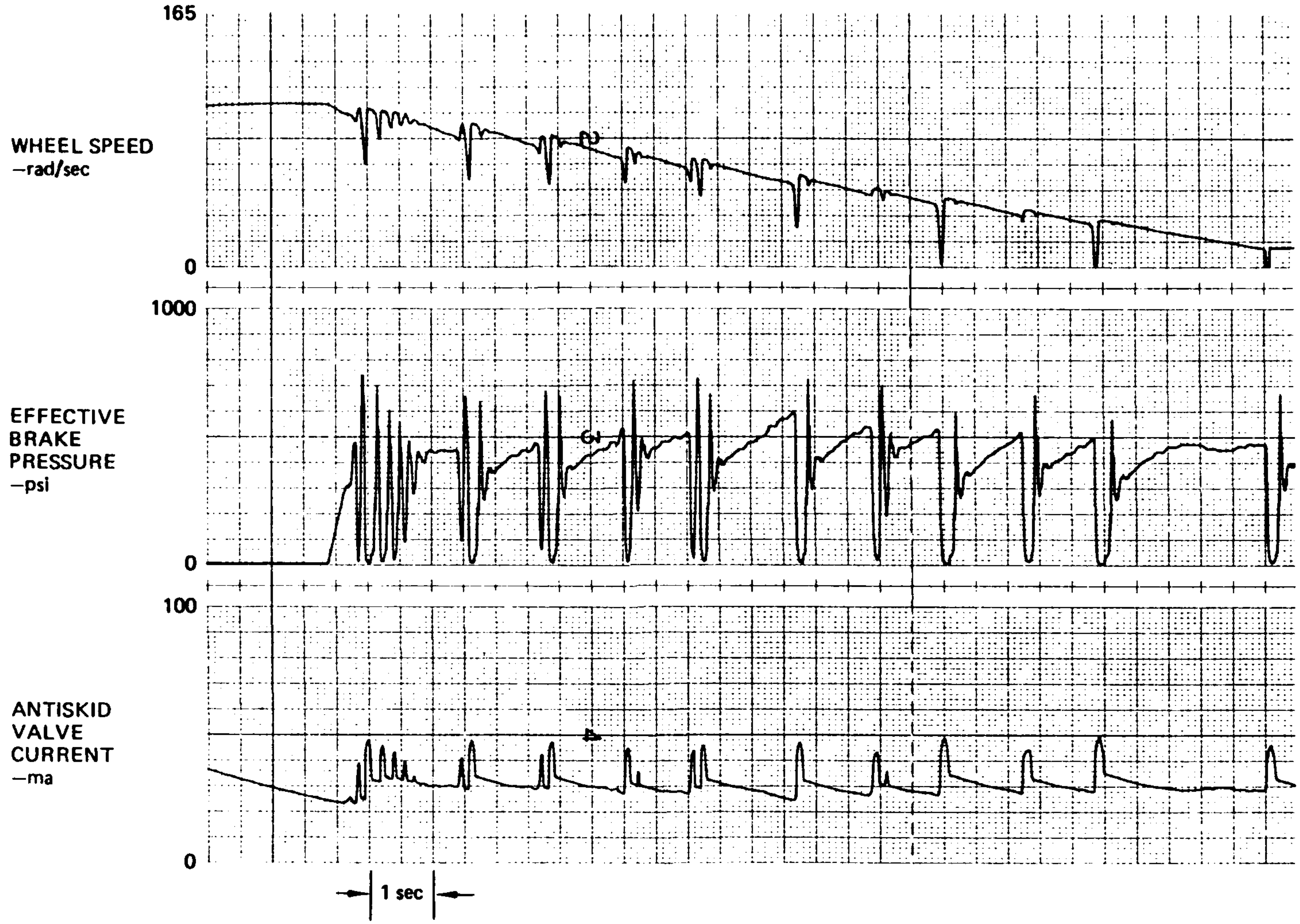


Figure D.26. As-Built Brake System Performance at 160^{o} F, Mu = 0.6

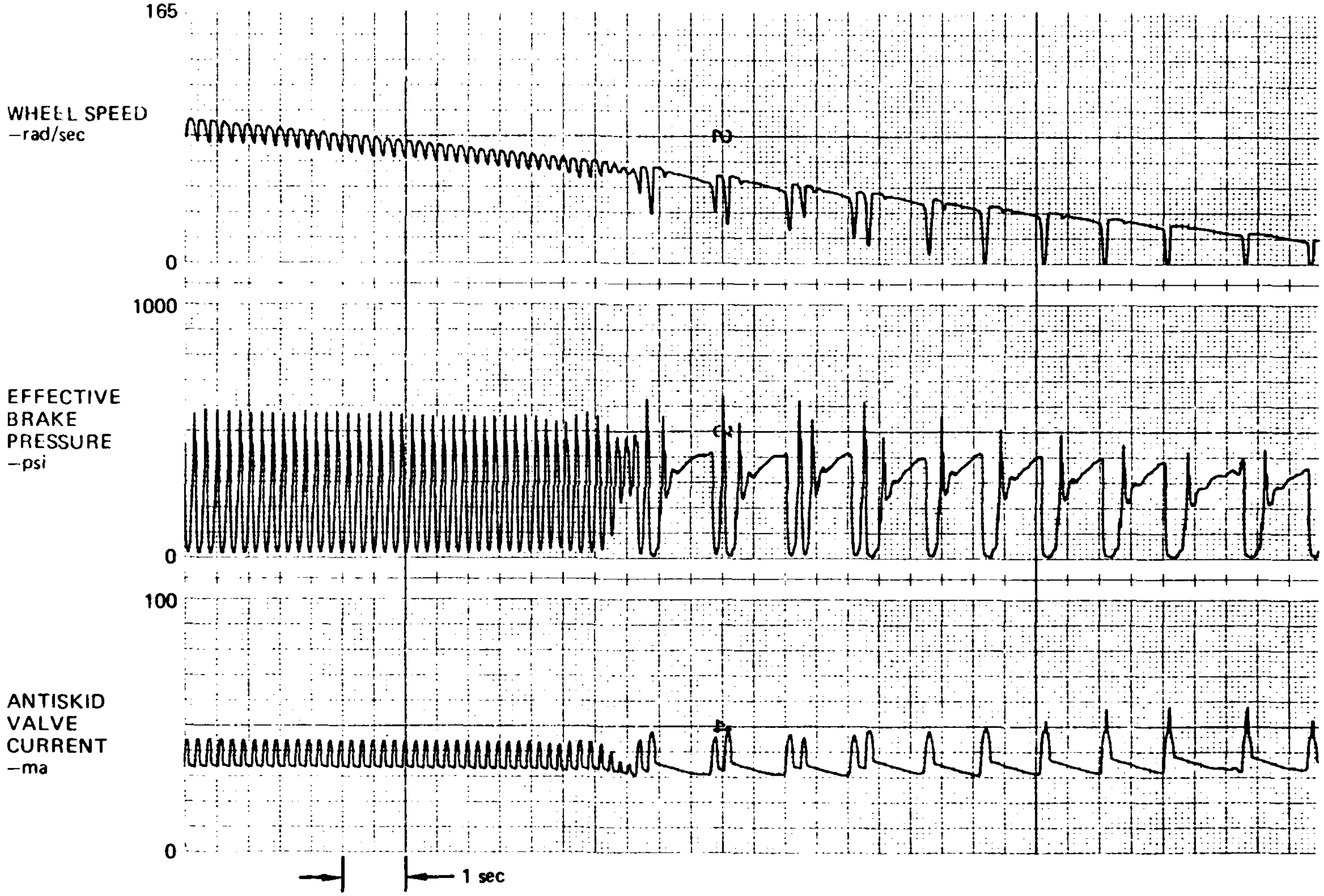


Figure D.27. As-Built Brake System Performance at 160°F, Mu = 0.5

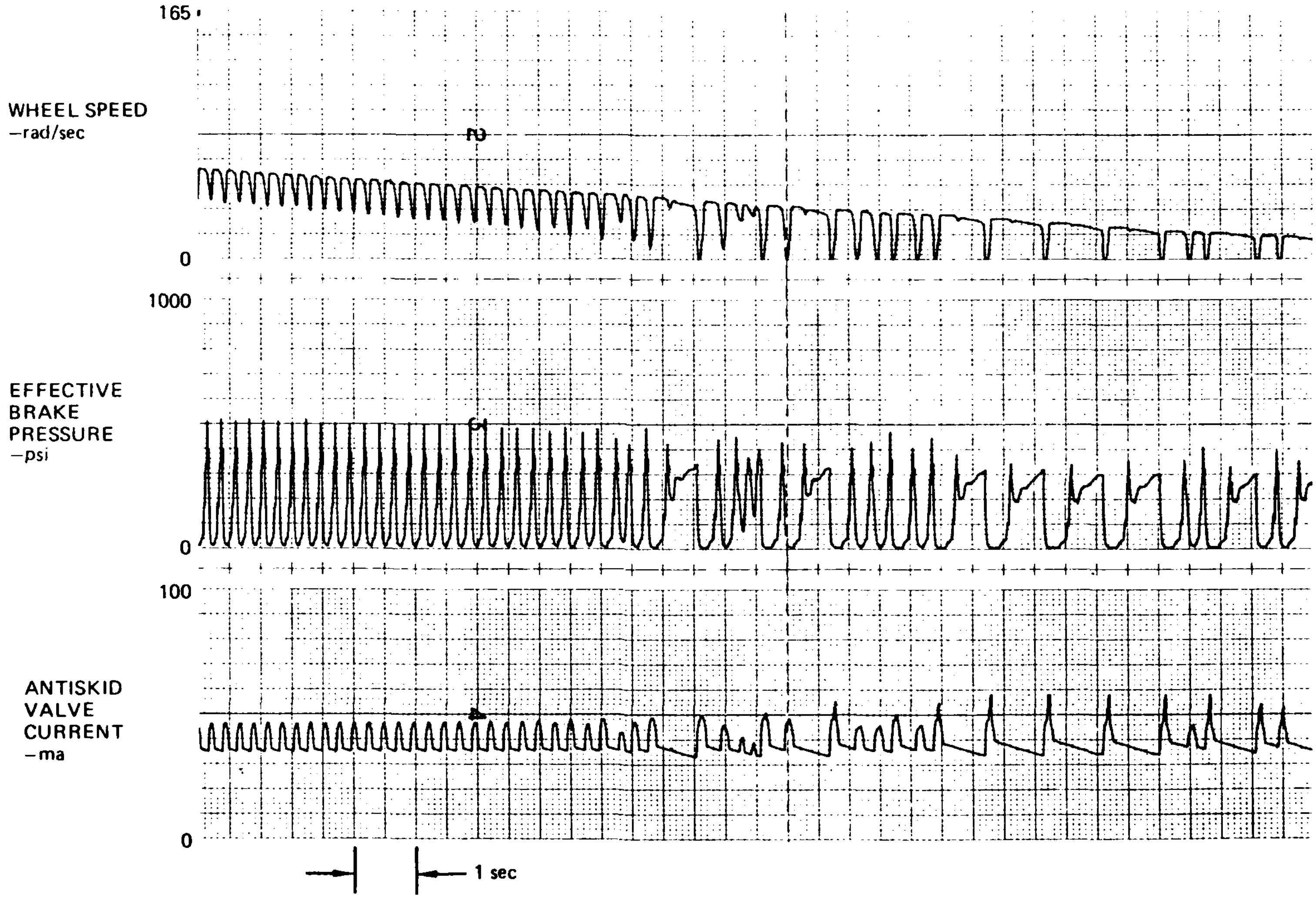


Figure D.28. As-Built Brake System Performance at 160°F, Mu = 0.4

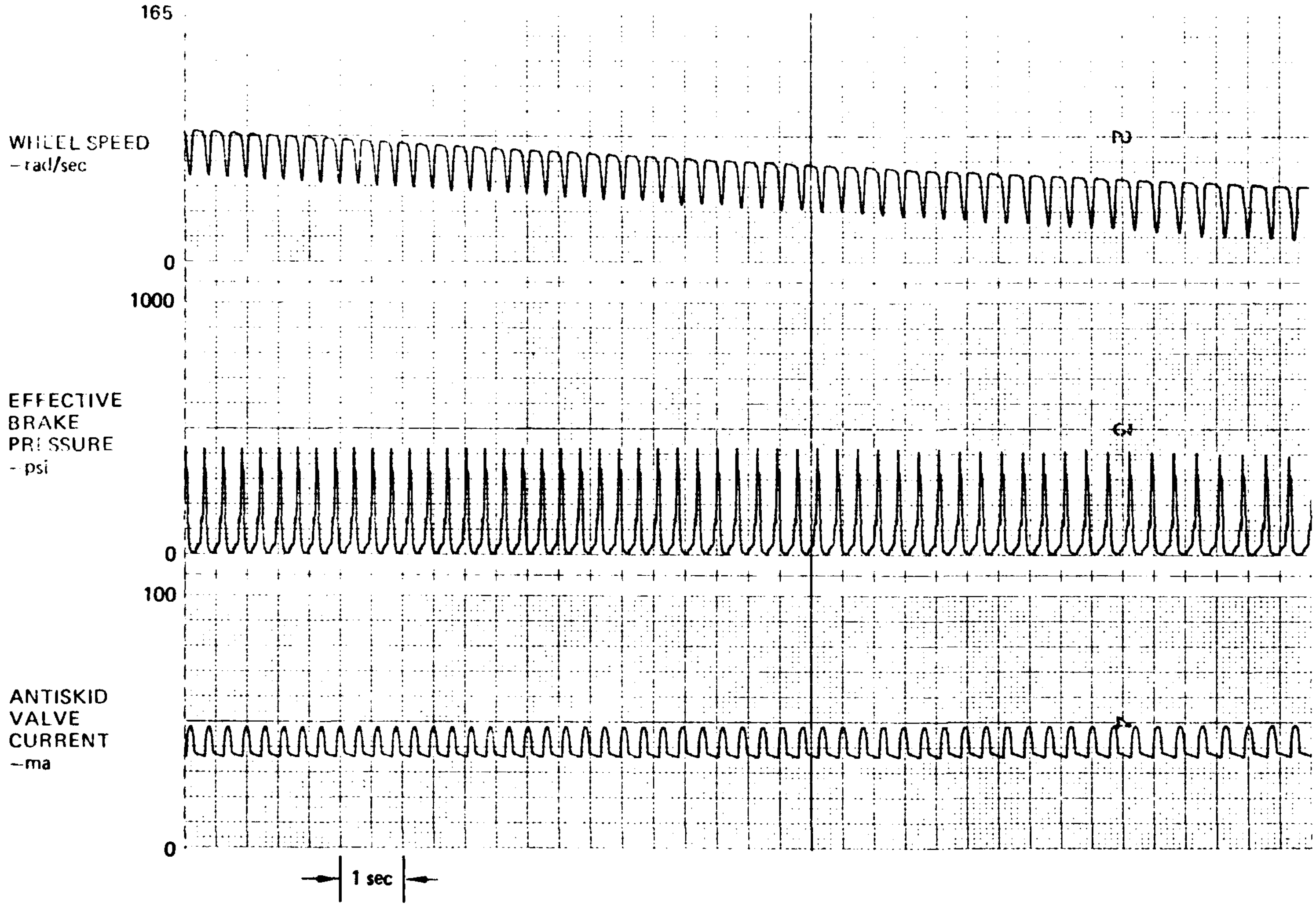


Figure D.29. As-Built Brake System Performance at 160°F, Mu = 0.3

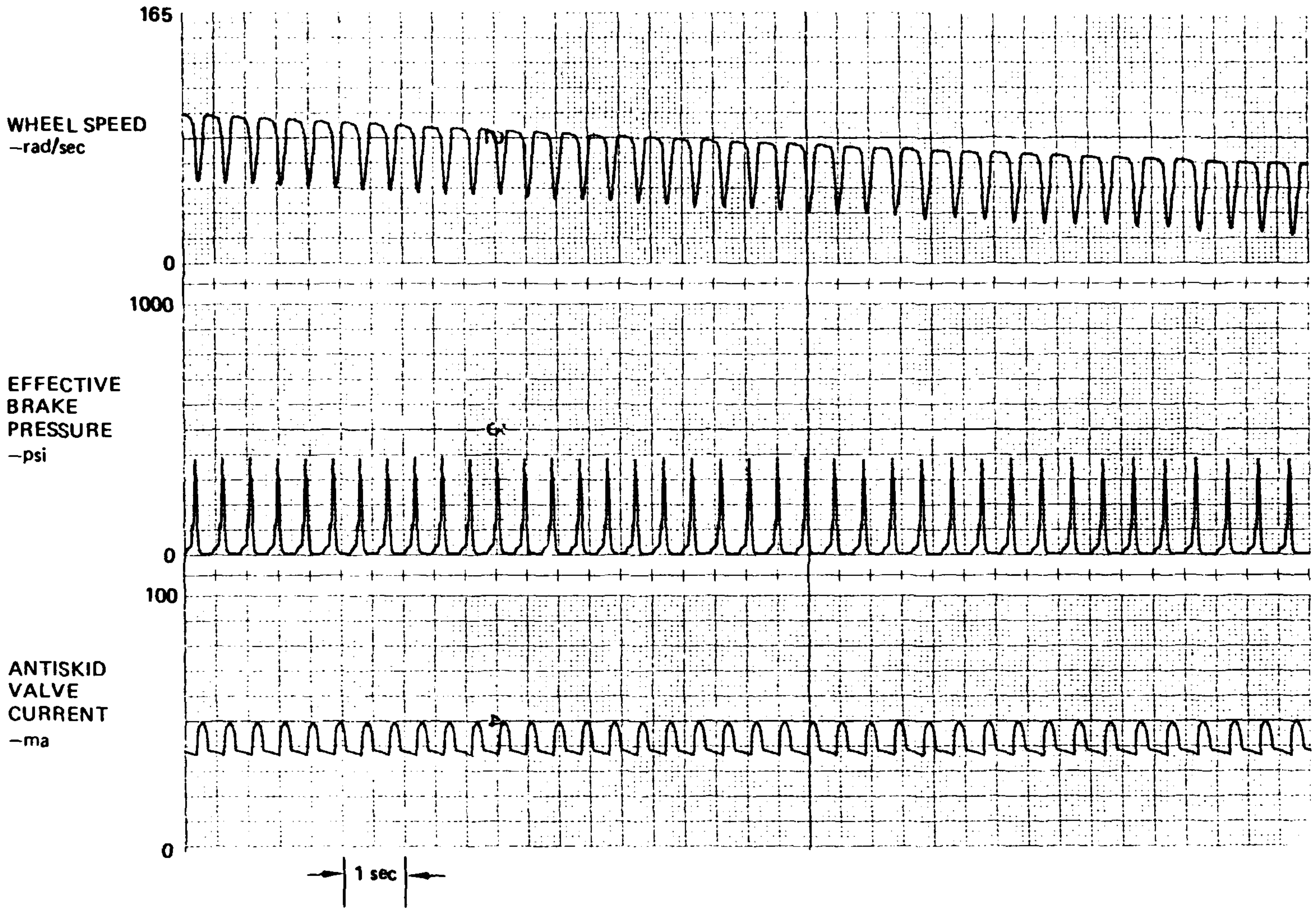


Figure D.30. As-Built Brake System Performance at 160°F, Mu = 0.2

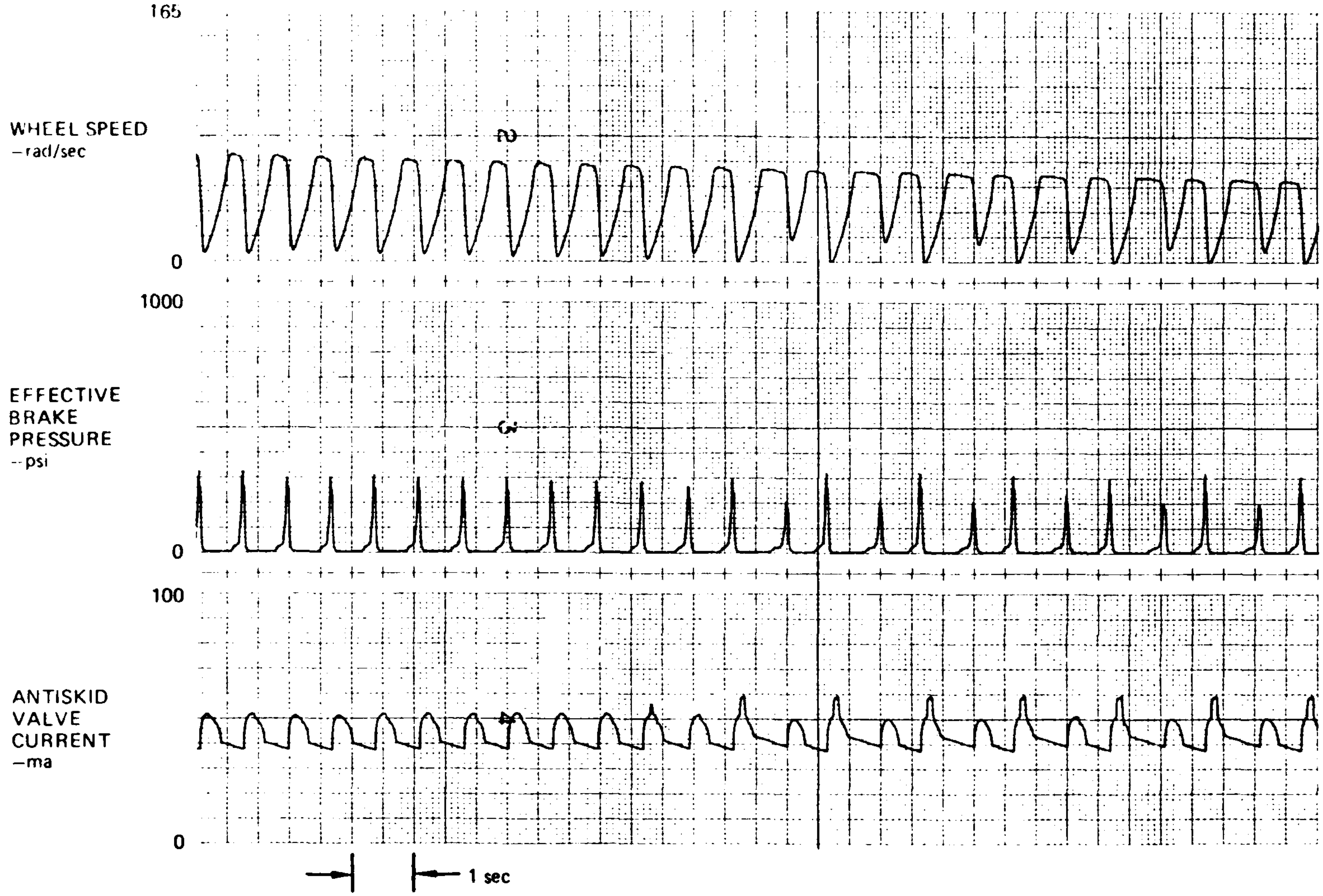


Figure D.31. As-built Brake System Performance at 160°F, Mu = 0.1

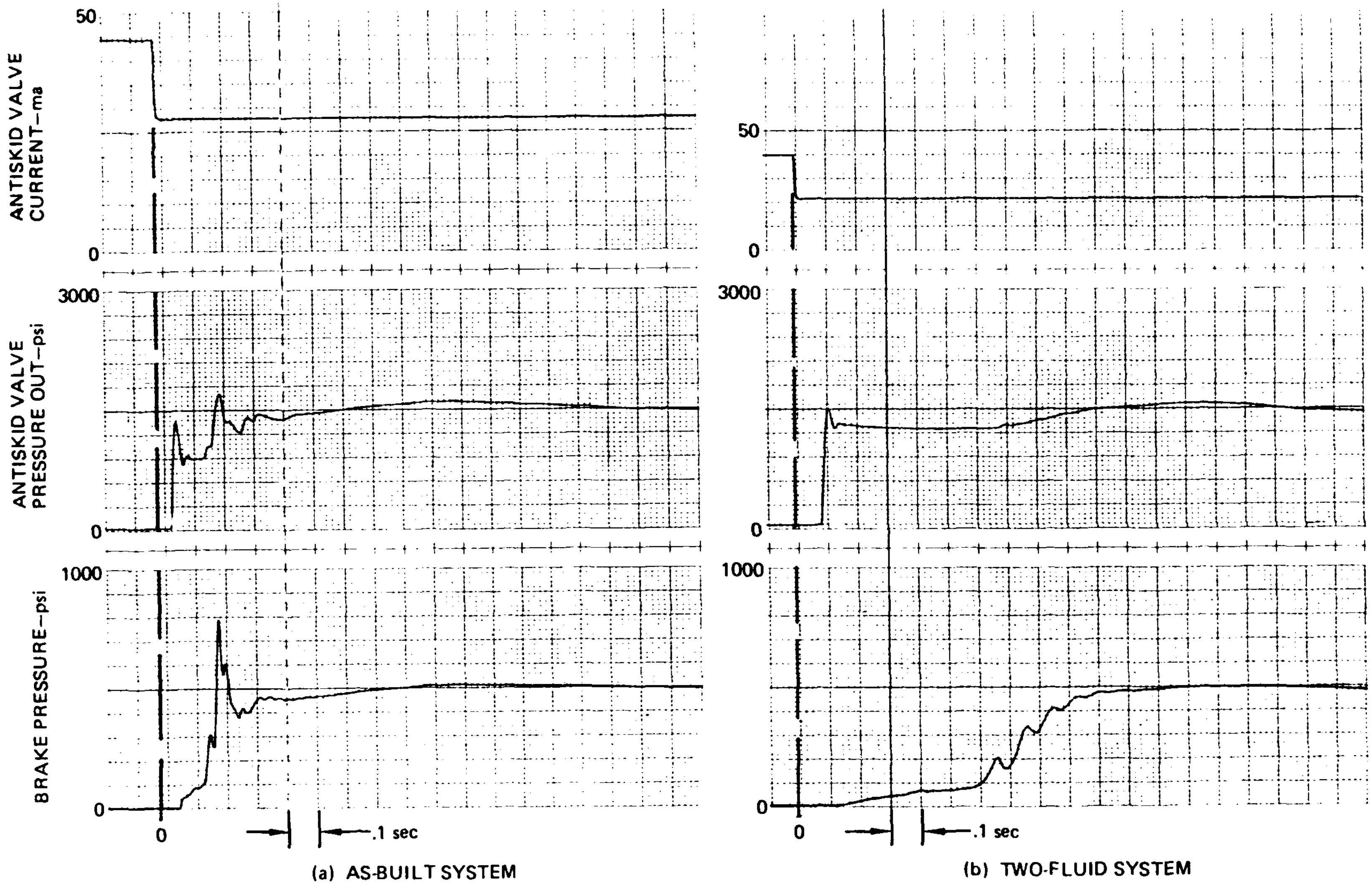


Figure D.32. System Response to Step Pressure Increase (0-50%) at 70°F

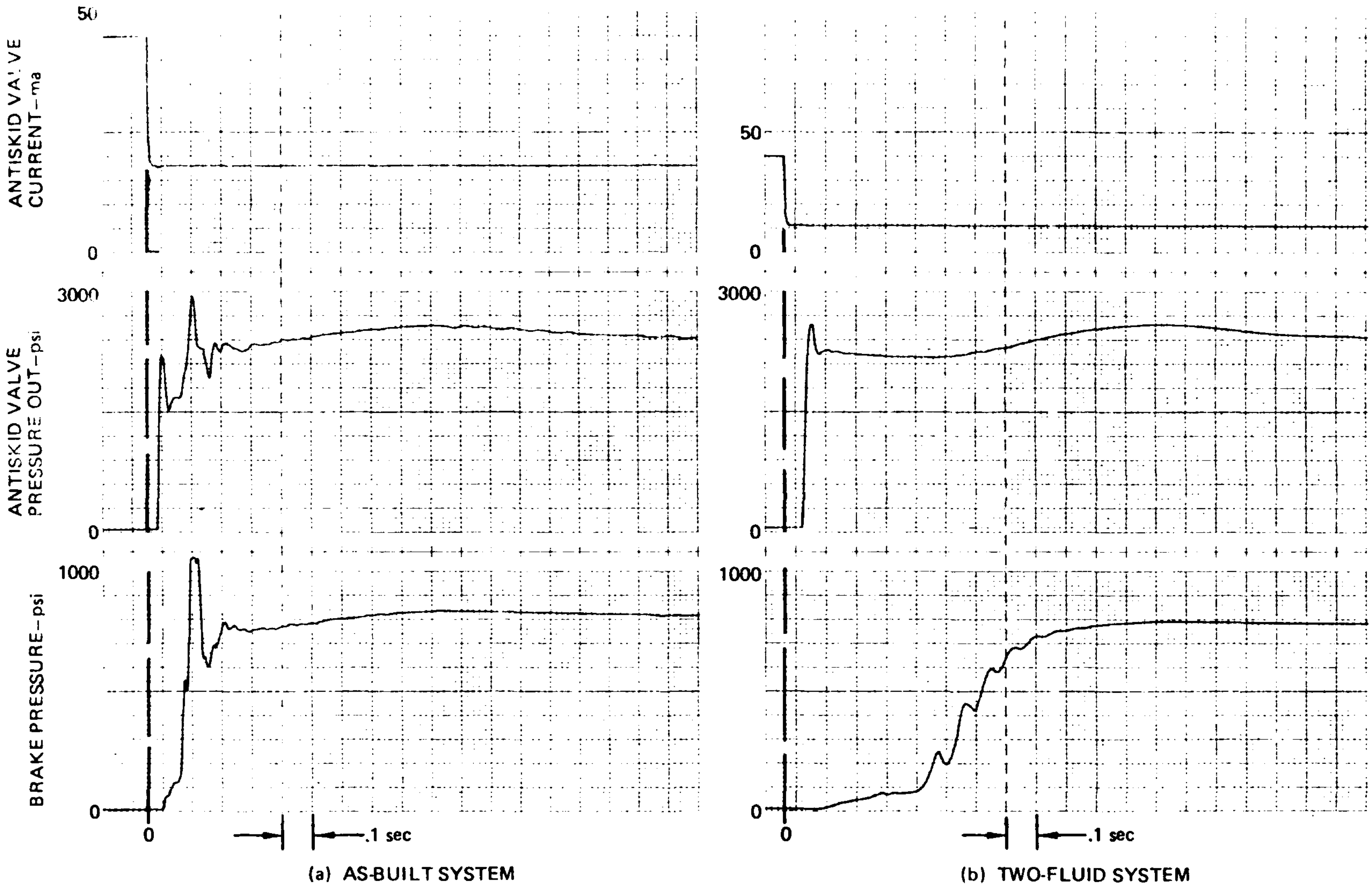


Figure D.33. System Response to Step Pressure Increase (0-80%) at 70°F

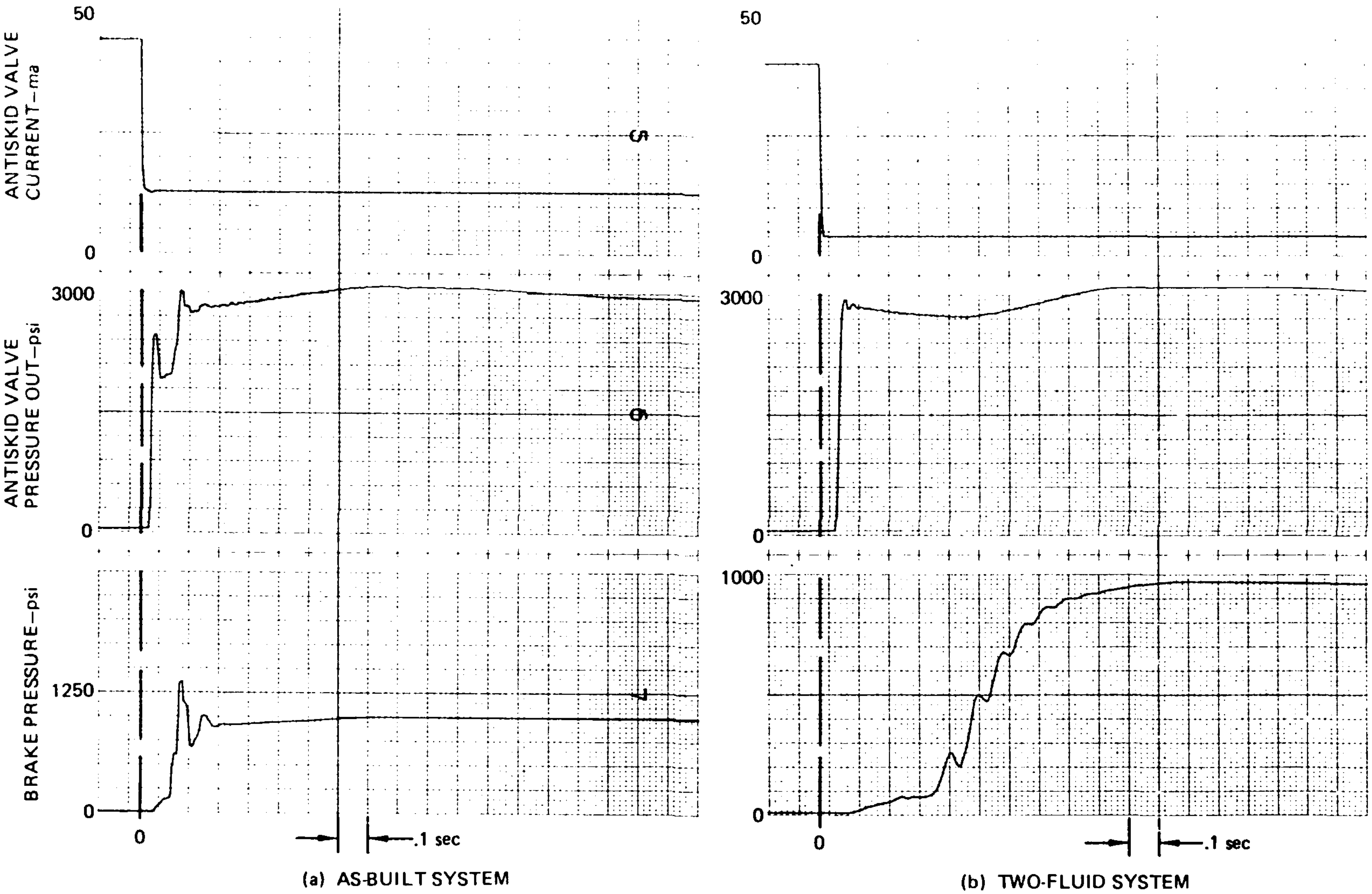


Figure D.34. System Response to Step Pressure Increase (0-100%) at 70^{0}F

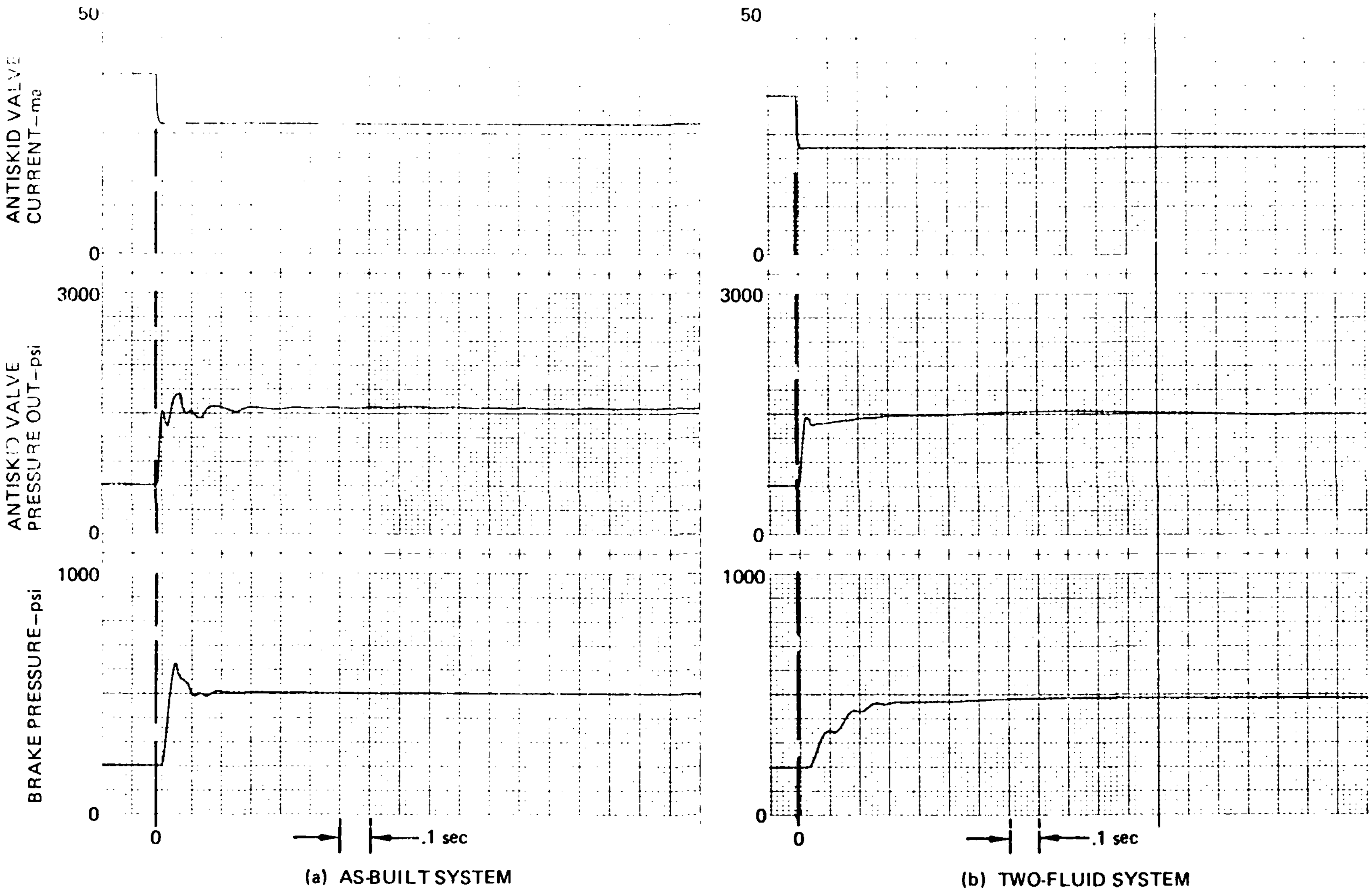


Figure D.35. System Response to Step Pressure Increase (20-50%) at 70^{o}F

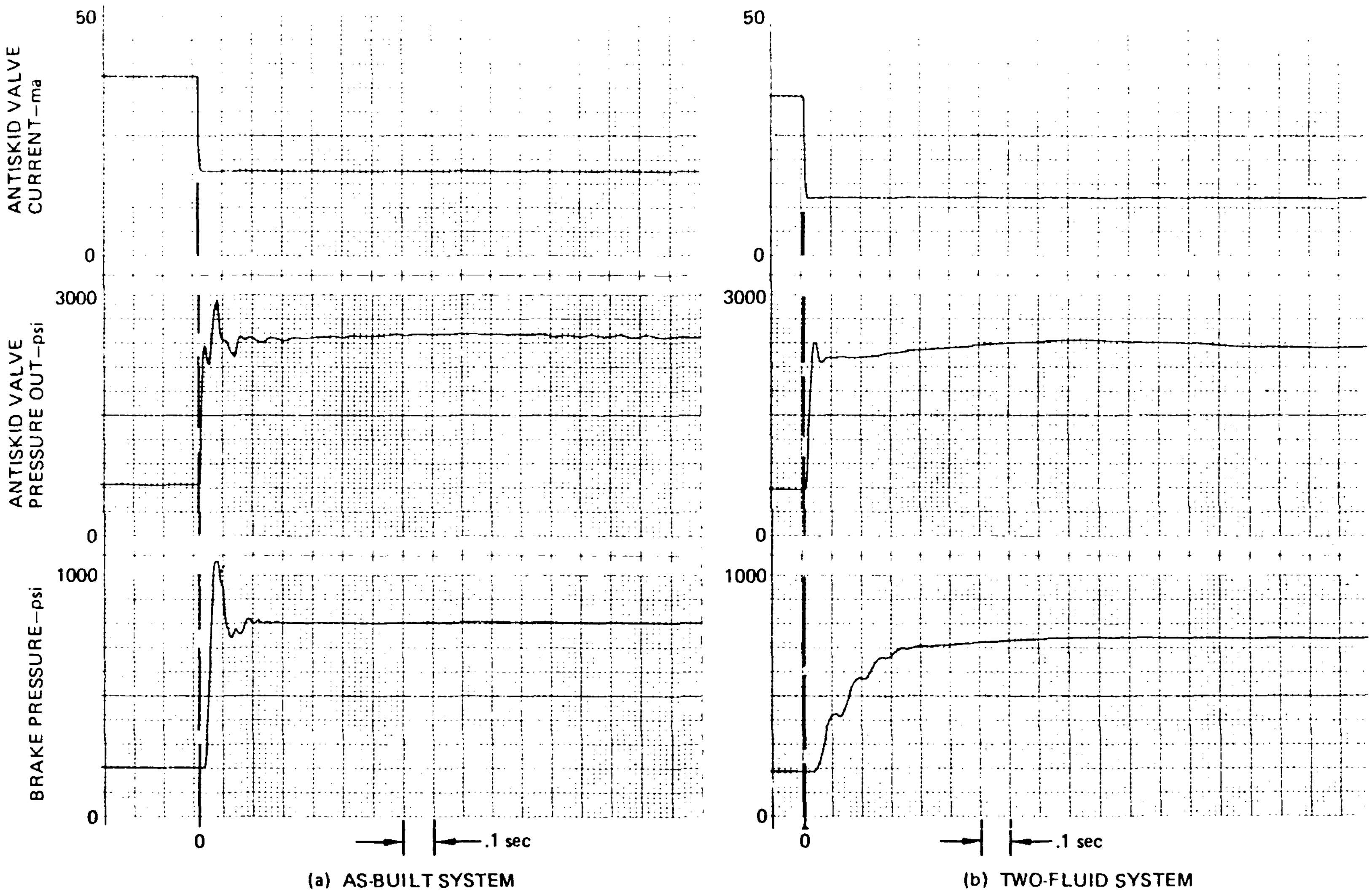


Figure D.36. System Response to Step Pressure Increase (20-80%) at 70°F

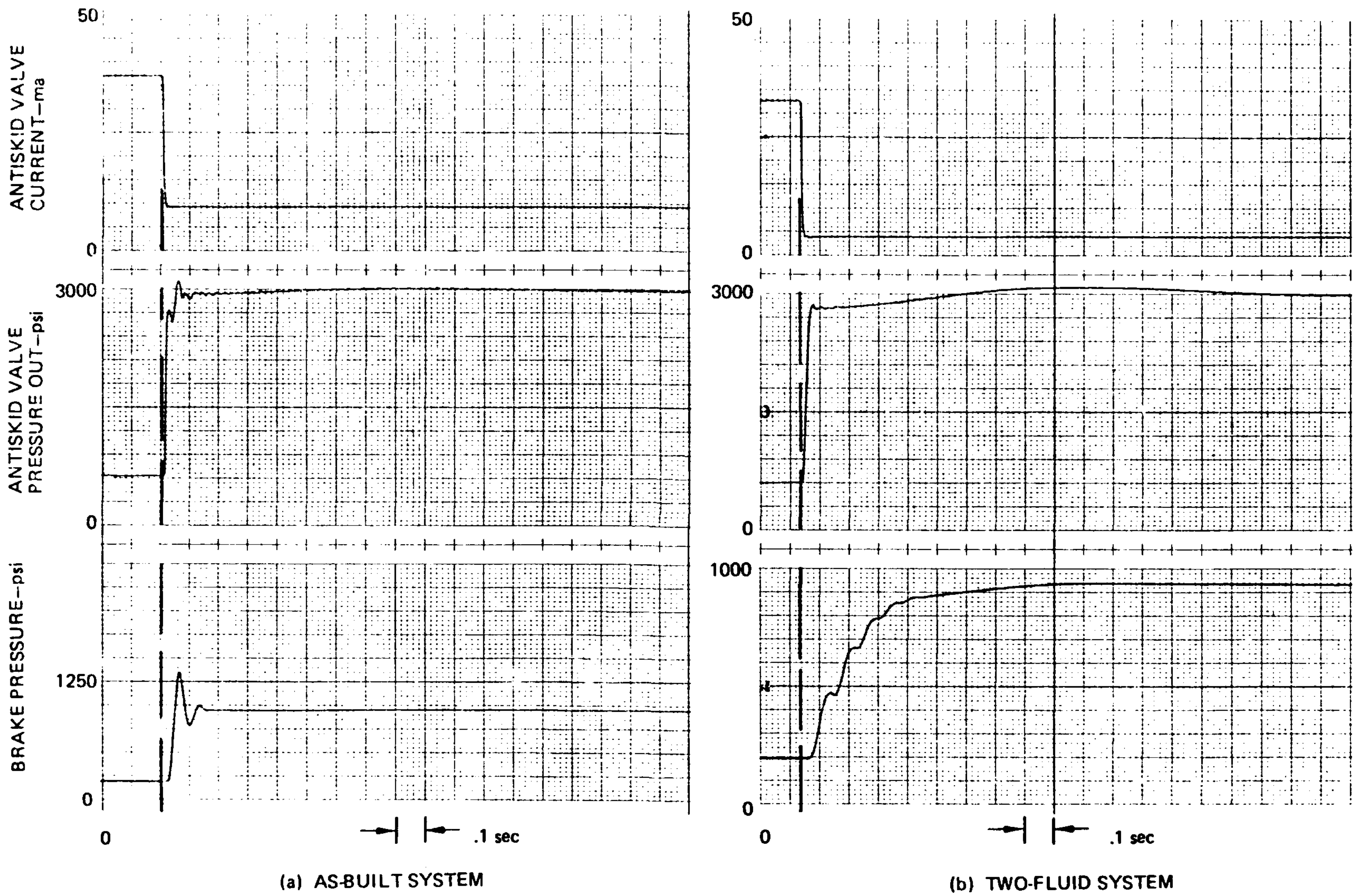


Figure D. 37. System Response to Step Pressure Increase (20-100%) at 70^{o}F

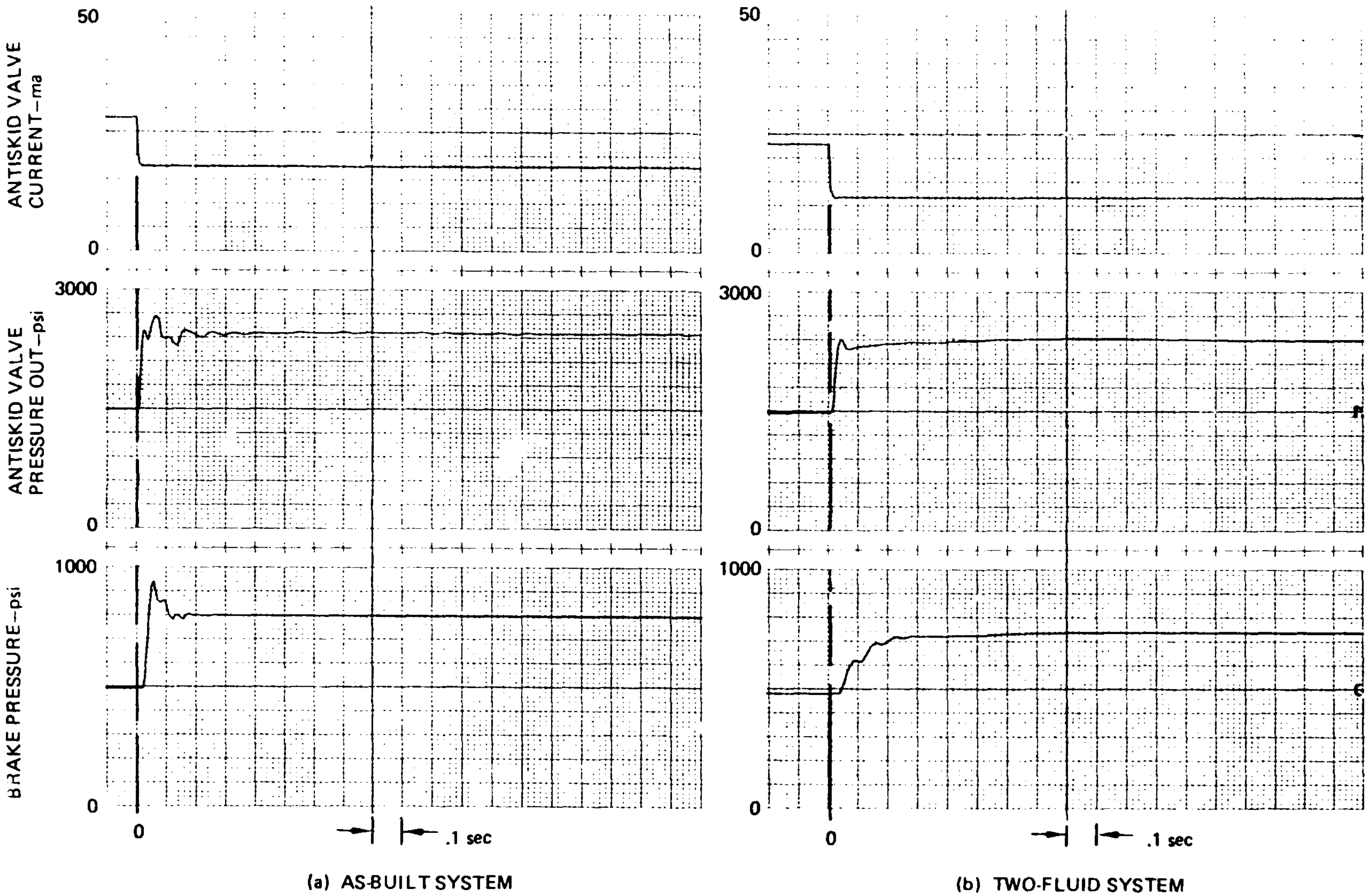
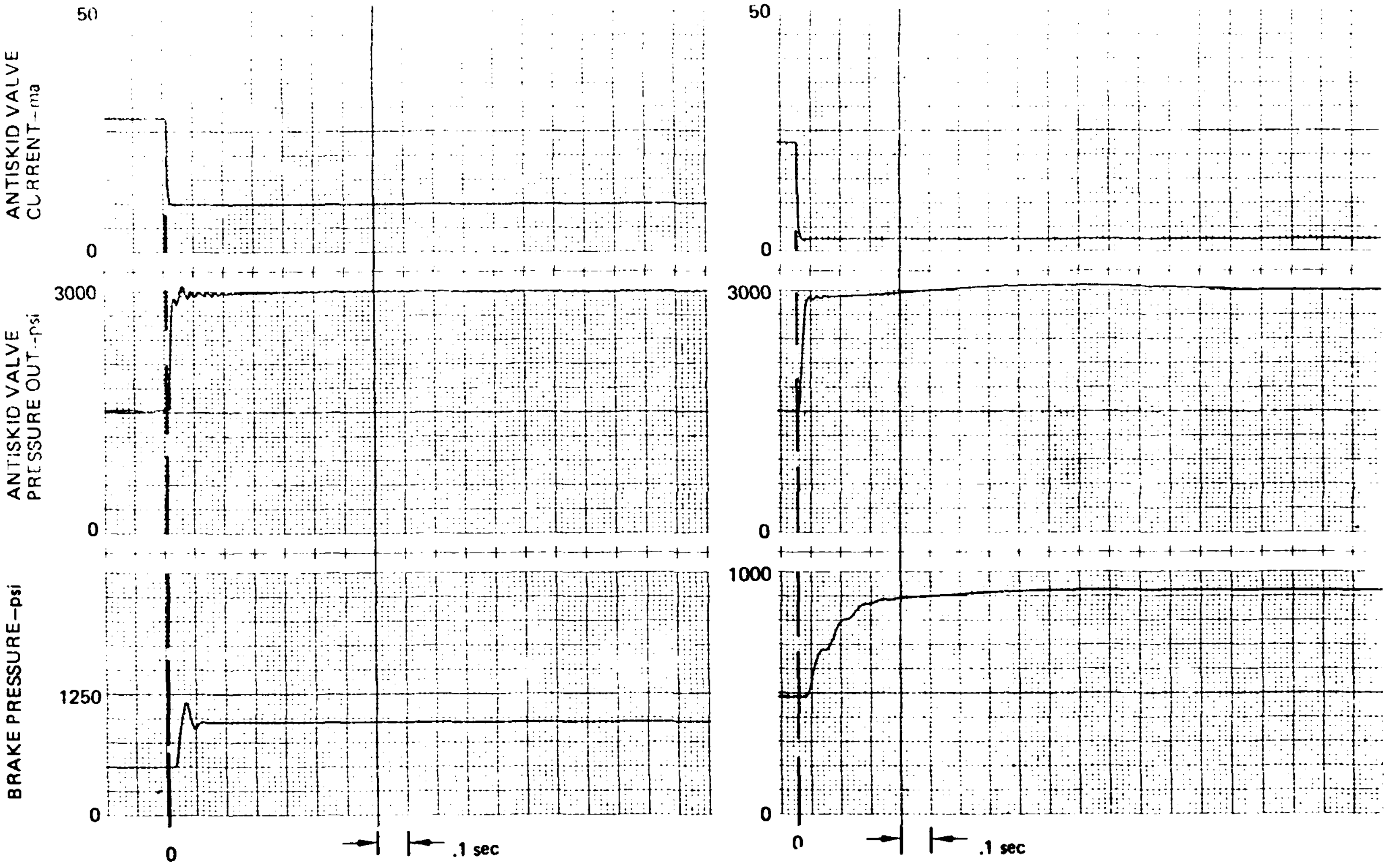


Figure D.38. System Response to Step Pressure Increase (50-80%) at 70^{o}F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.39. System Response to step Pressure Increase (50-100%) at 70°F

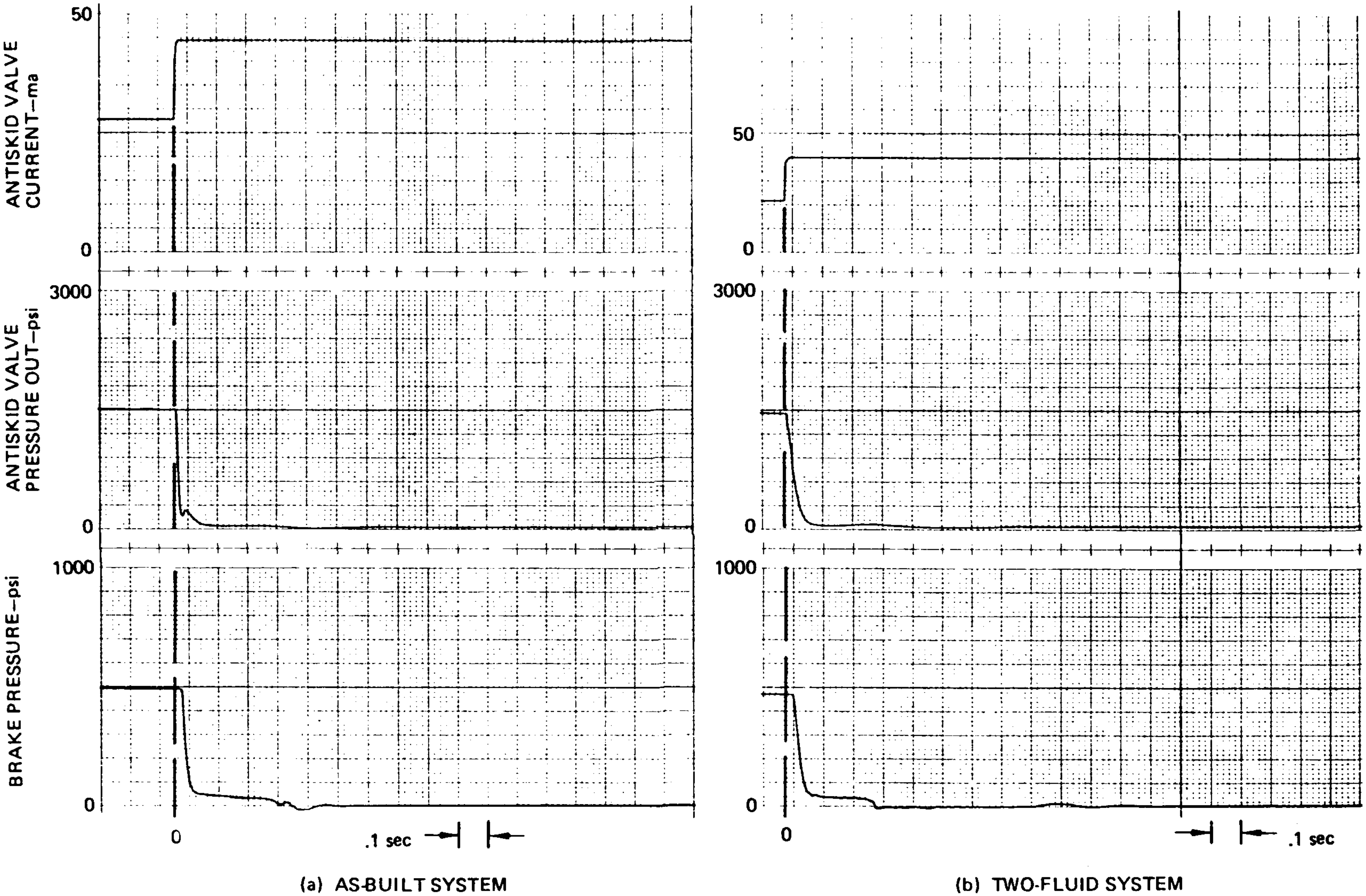


Figure D.40. System Response to Step Pressure Decrease (50-0%) at $70^{o}F$

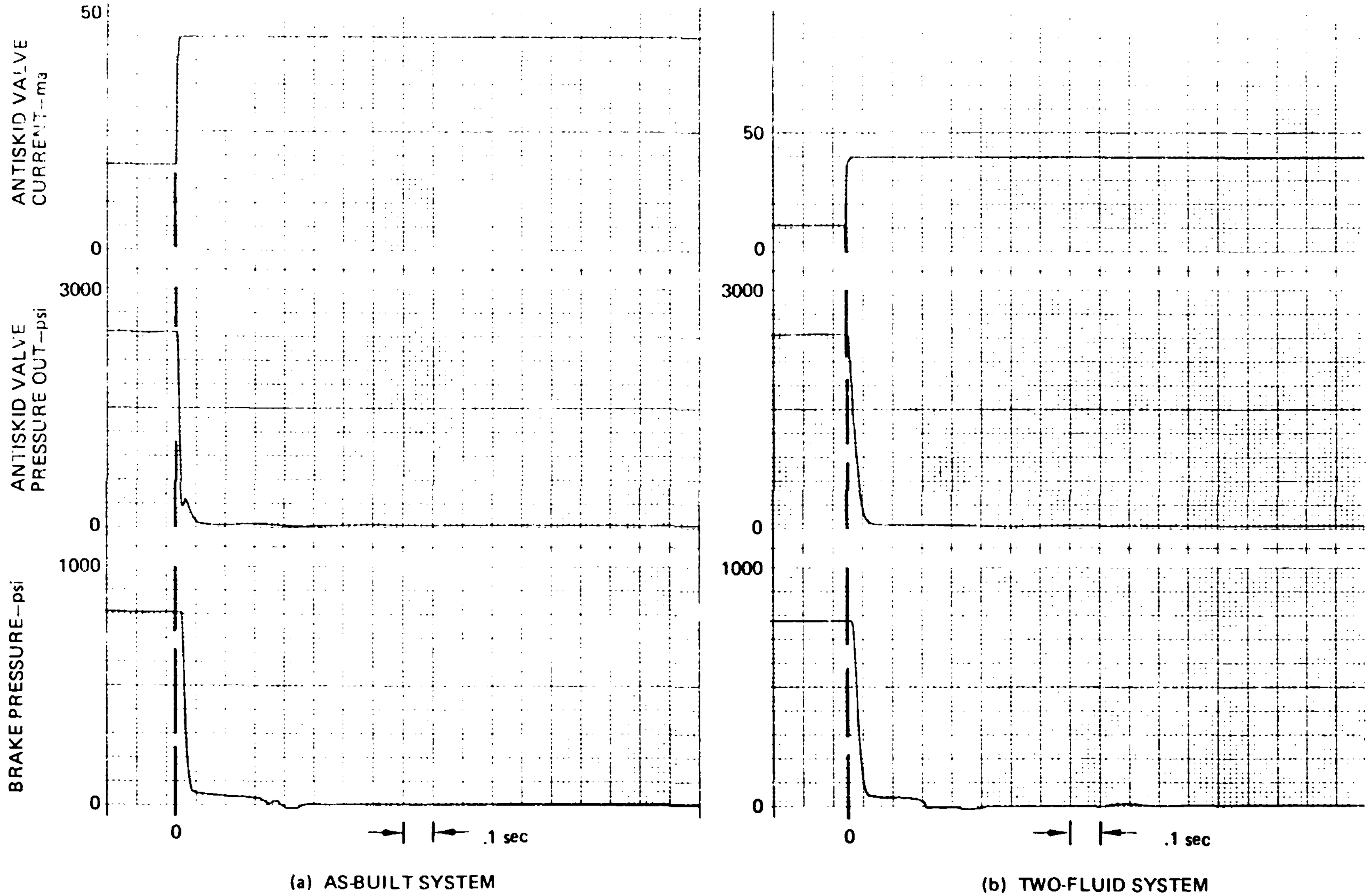


Figure D.41. System Response to Step Pressure Decrease (80-0%) at 70^{o}F

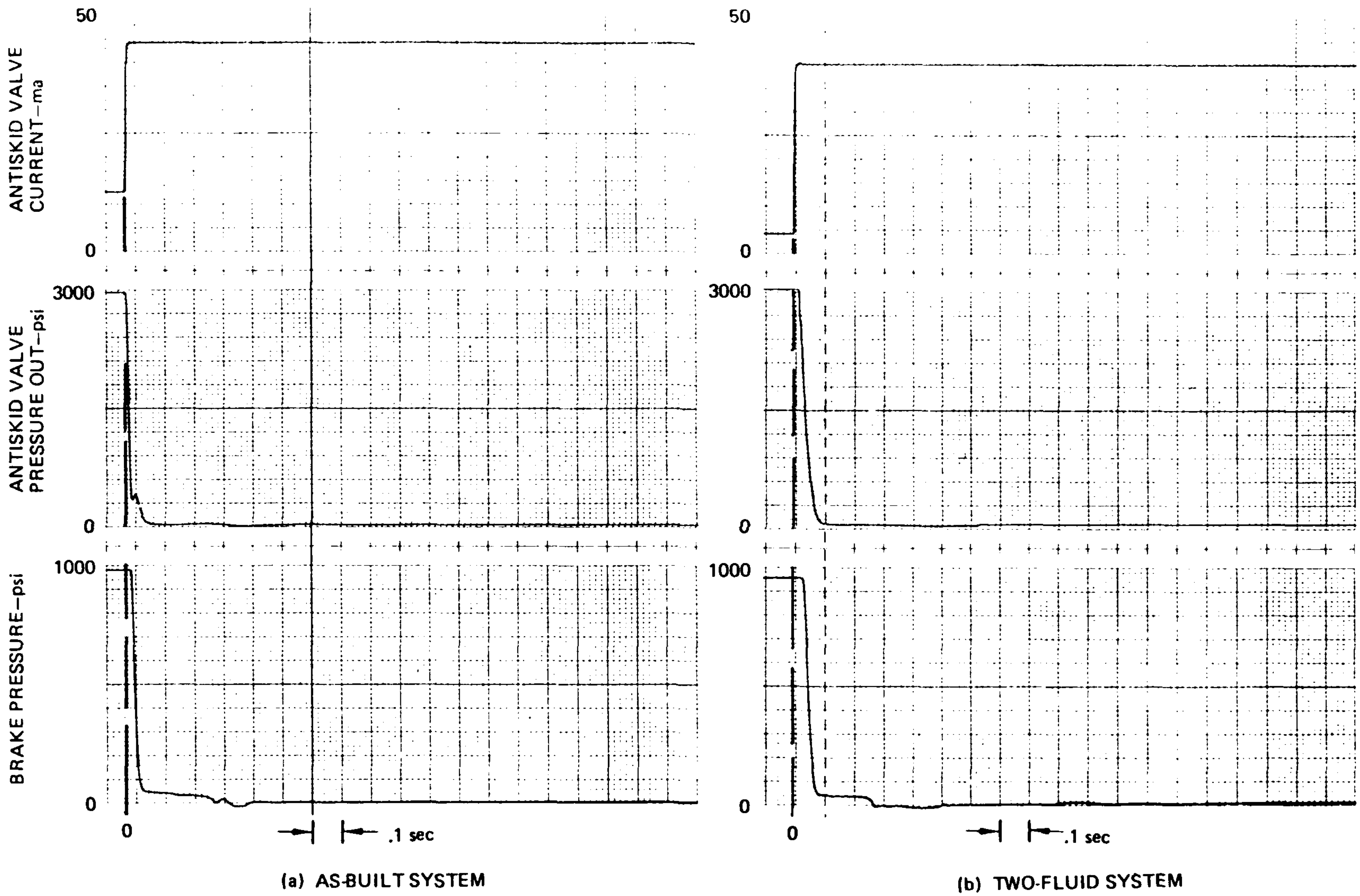
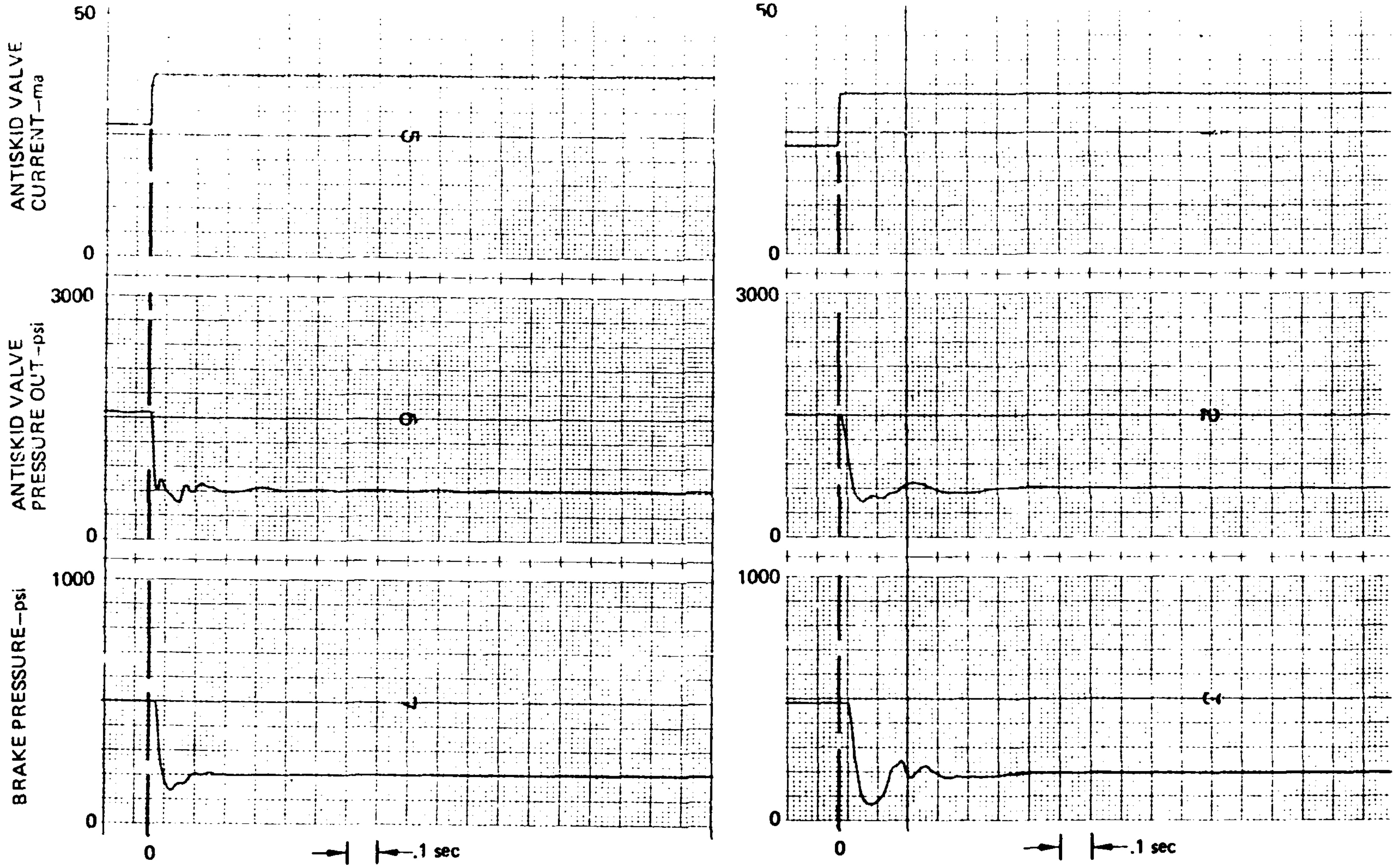


Figure D.42. System Response to Step Pressure Decrease (100-0%) at 70^{o}F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.43. System Response to Step Pressure Decrease (50-20%) at 70^{o}F

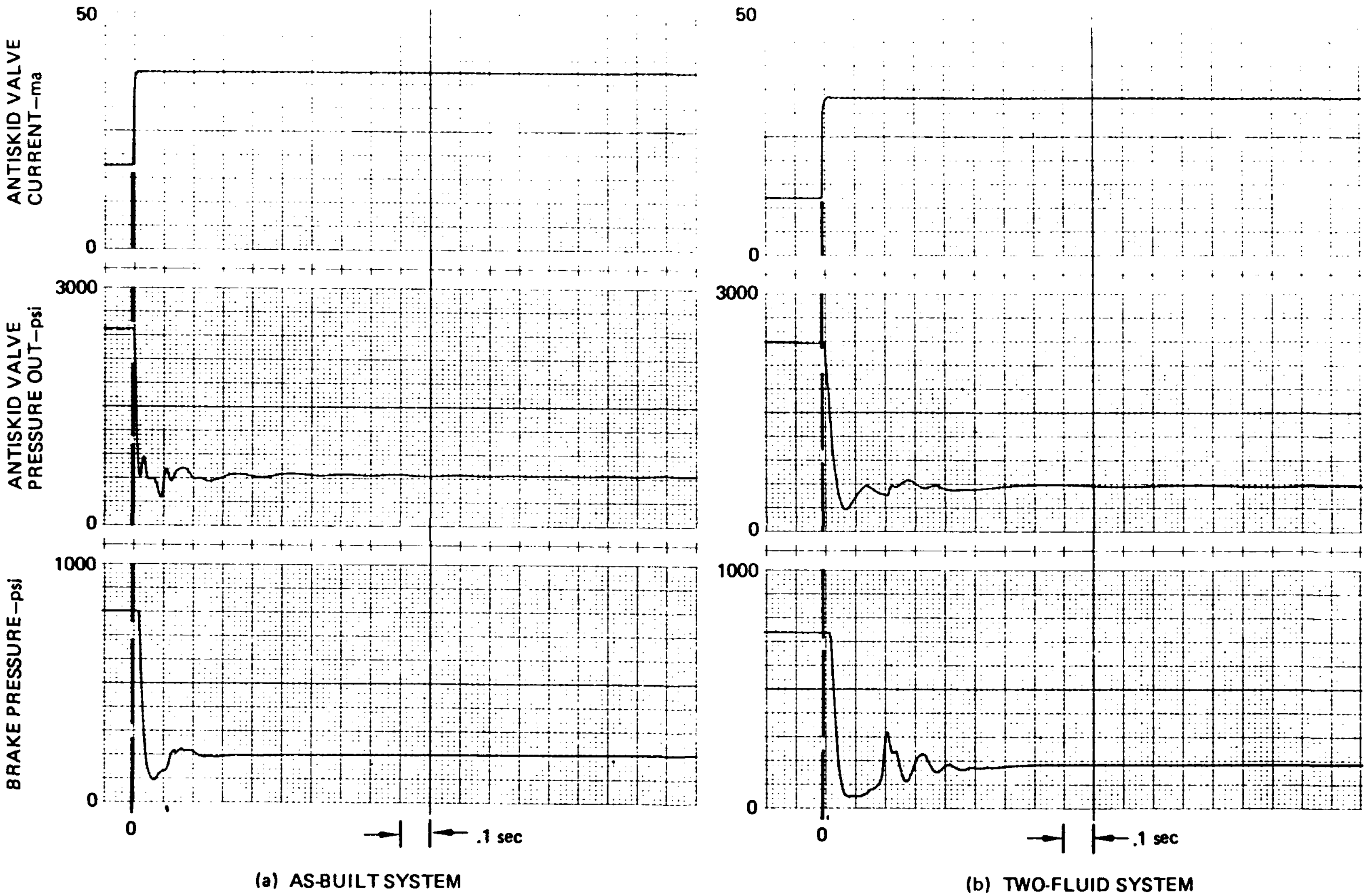


Figure D.44. System Response to Step Pressure Decrease (80-20%) at 70°F

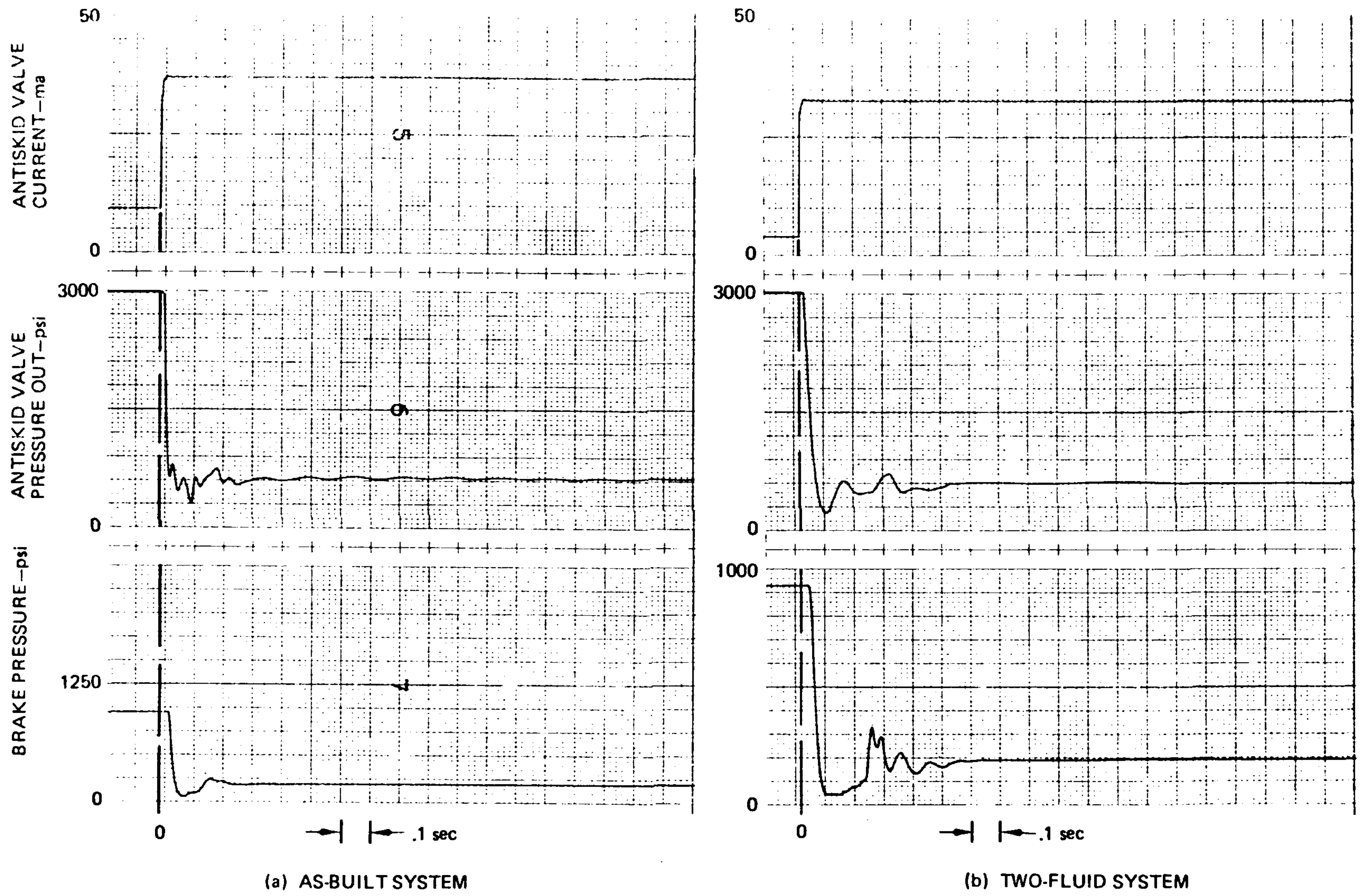


Figure D.45. System Response to Step Pressure Decrease (100-20%) at 70^{o}F

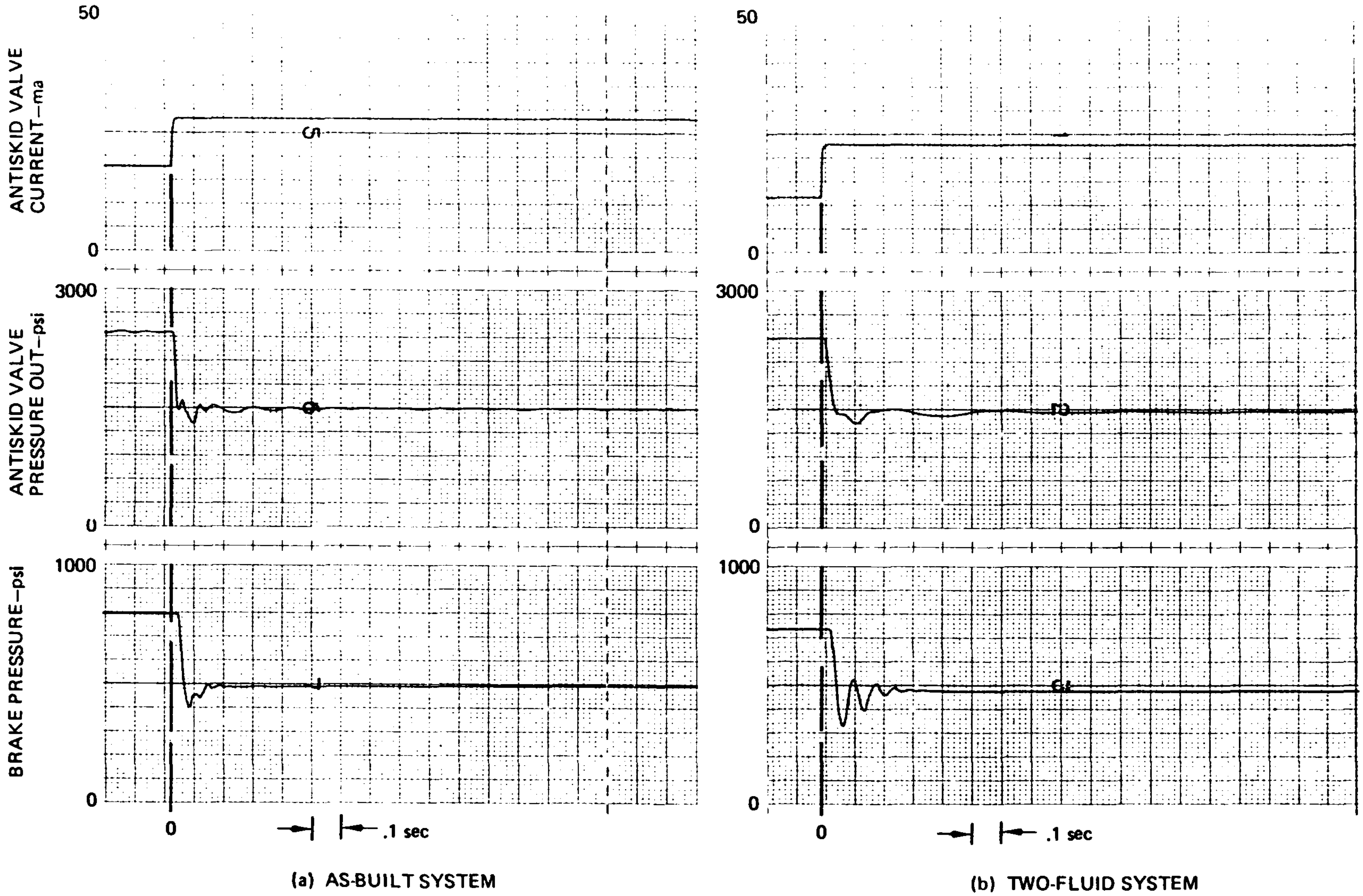


Figure D.46. System Response to Step Pressure Decrease (80-50%) at 70^{o} F

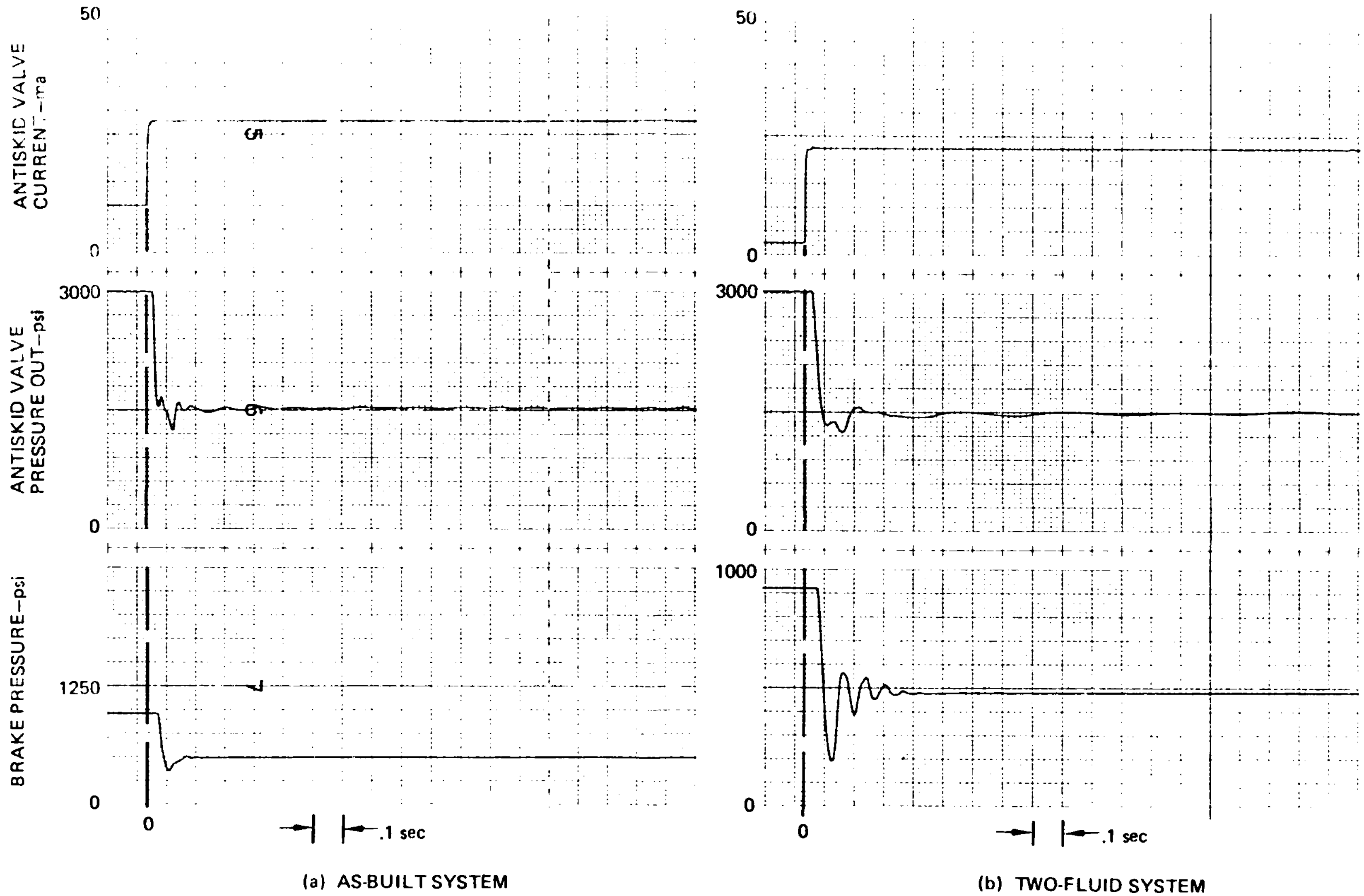


Figure D.47. System Response to Step Pressure Decrease (100-50%) at 70°F

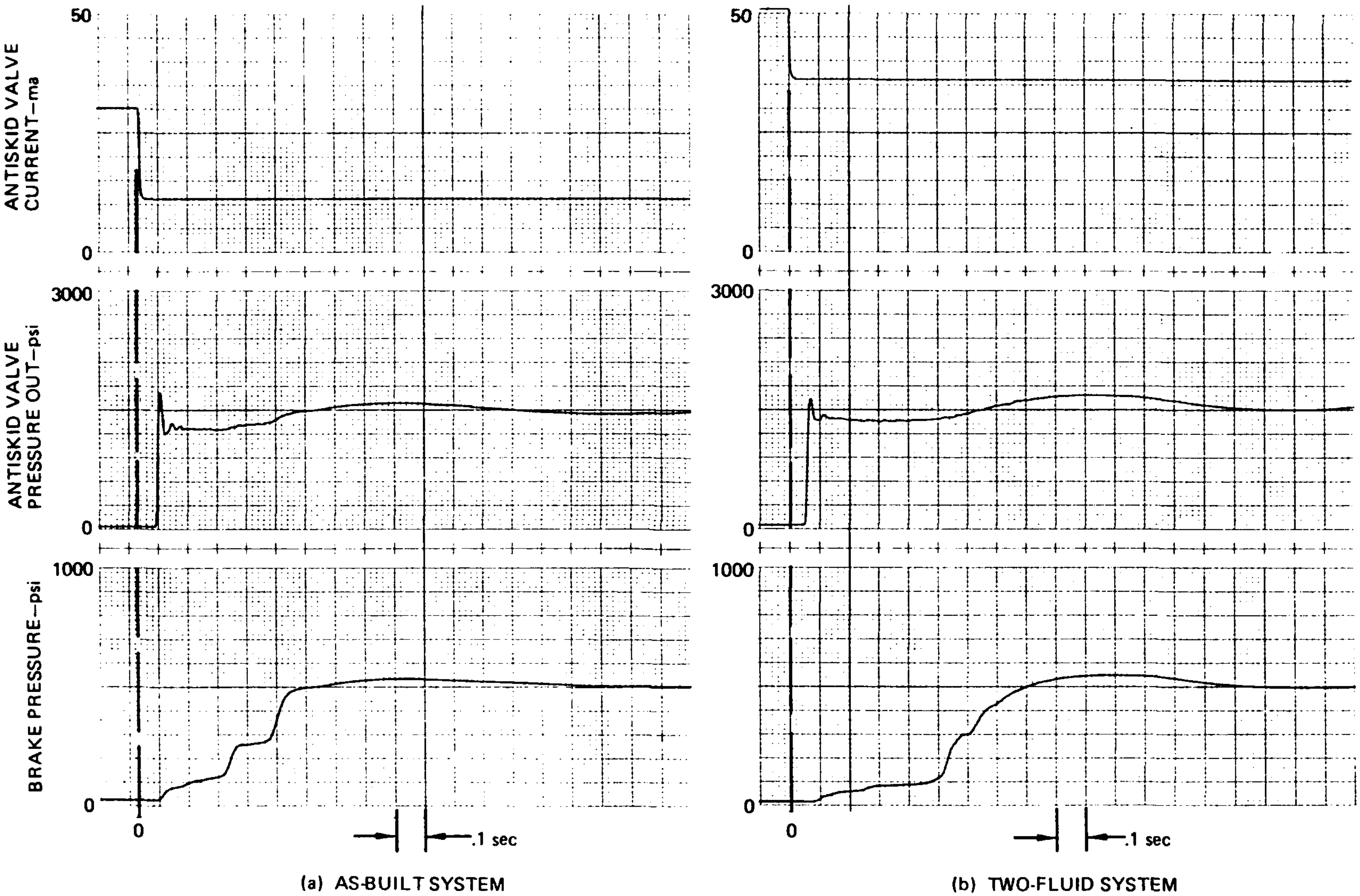


Figure D.48. System Response to Step Pressure Increase (0-50%) at -40^{o} F

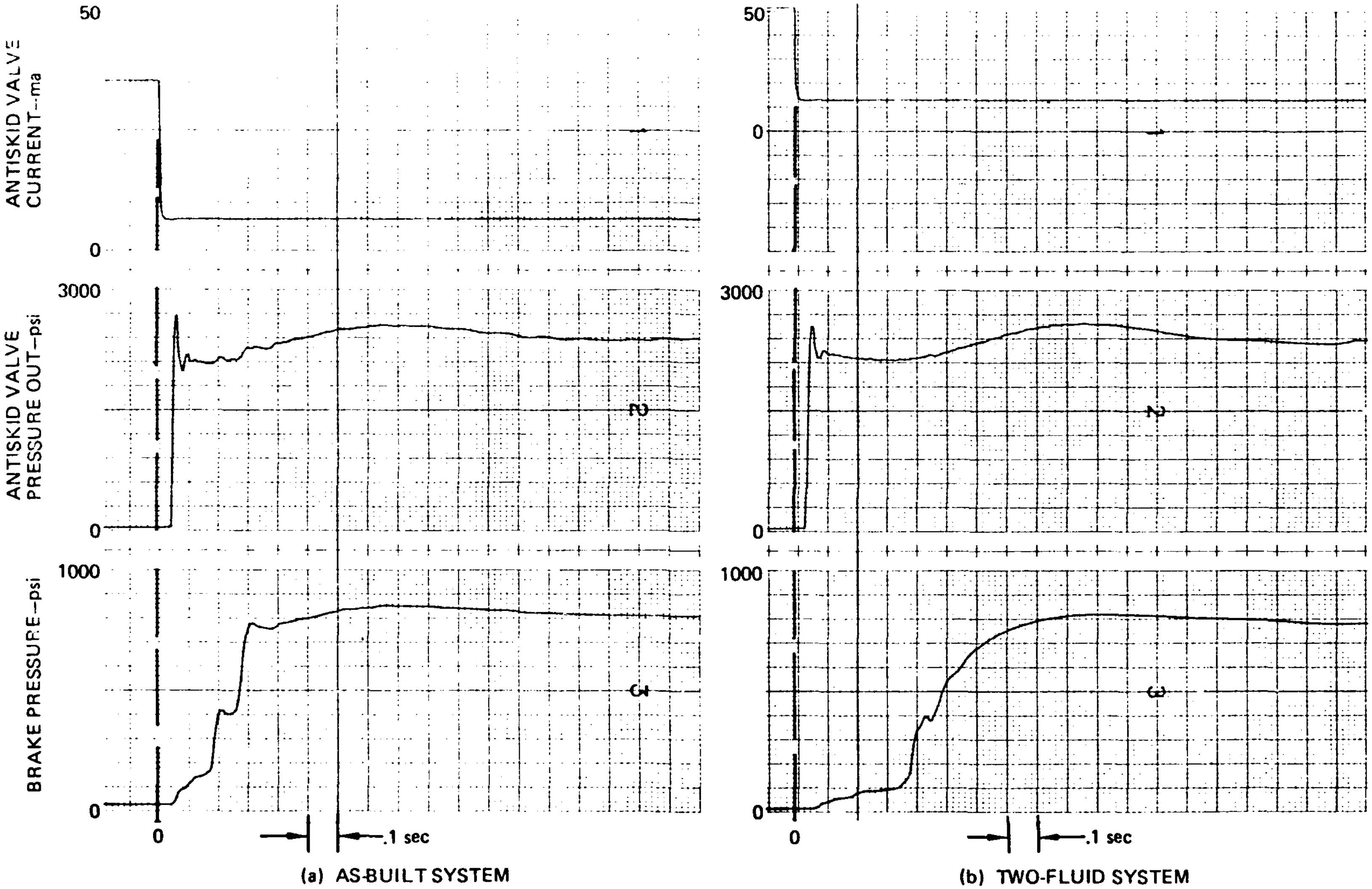


Figure D.49. System Response to Step Pressure Increase (0-80%) at -40°F

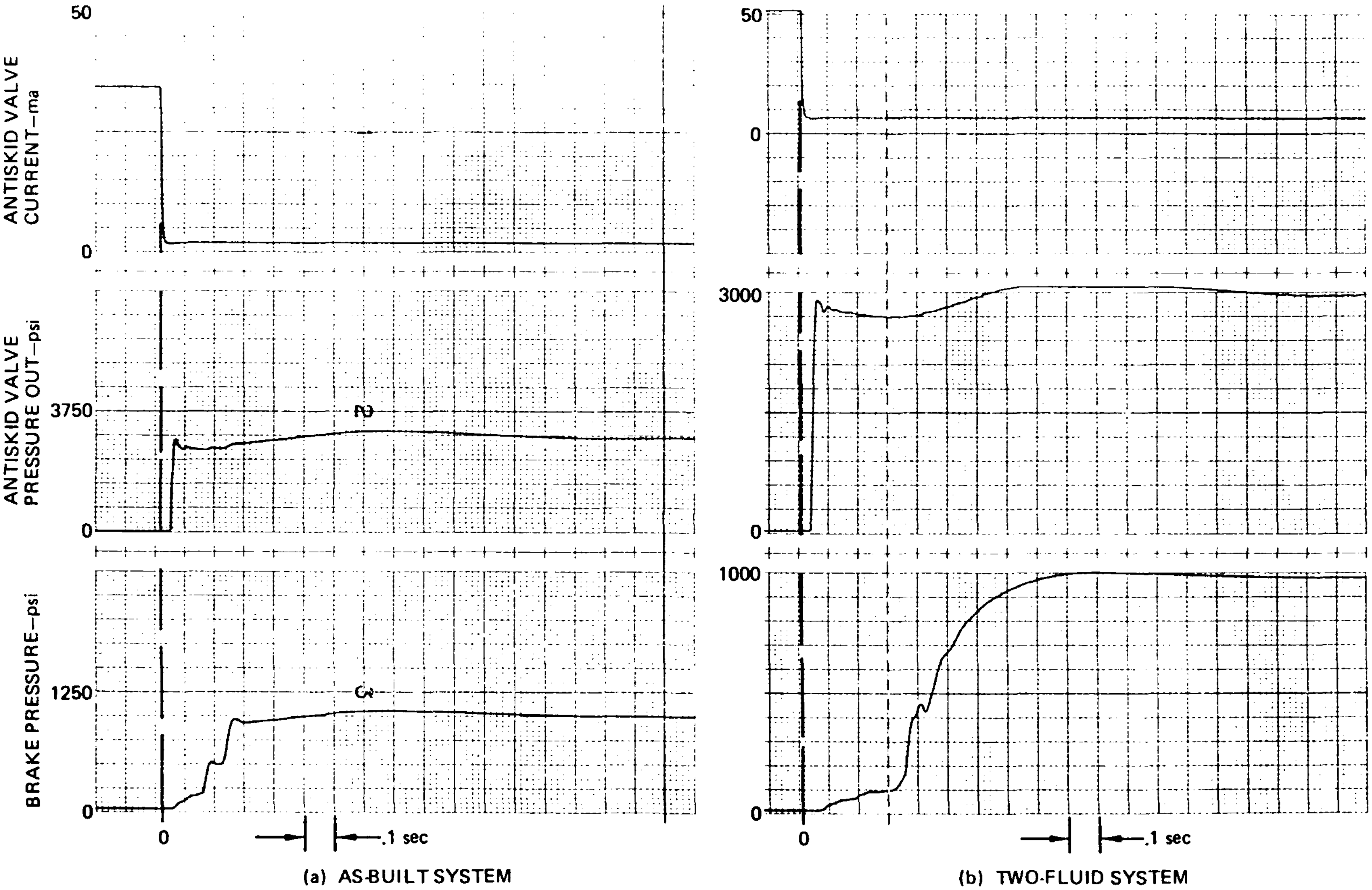
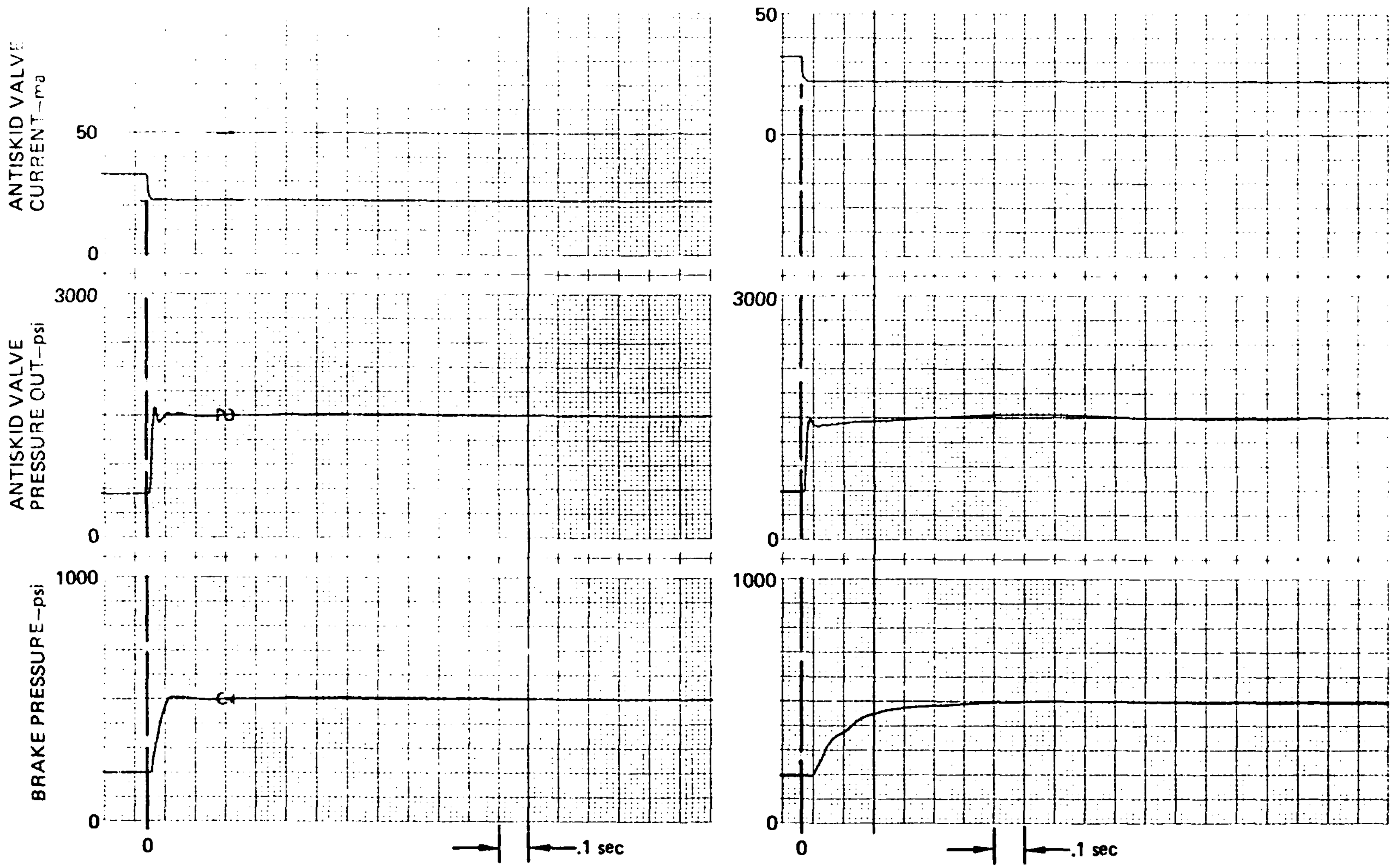


Figure D.50. System Response to Step Pressure Increase (0-100%) at -40^{o}F



(a) AS-BUILT SYSTEM (b) TWO-FLUID SYSTEM

Figure D.51. System Response to Step Pressure Increase (20-50%) at -40 °F

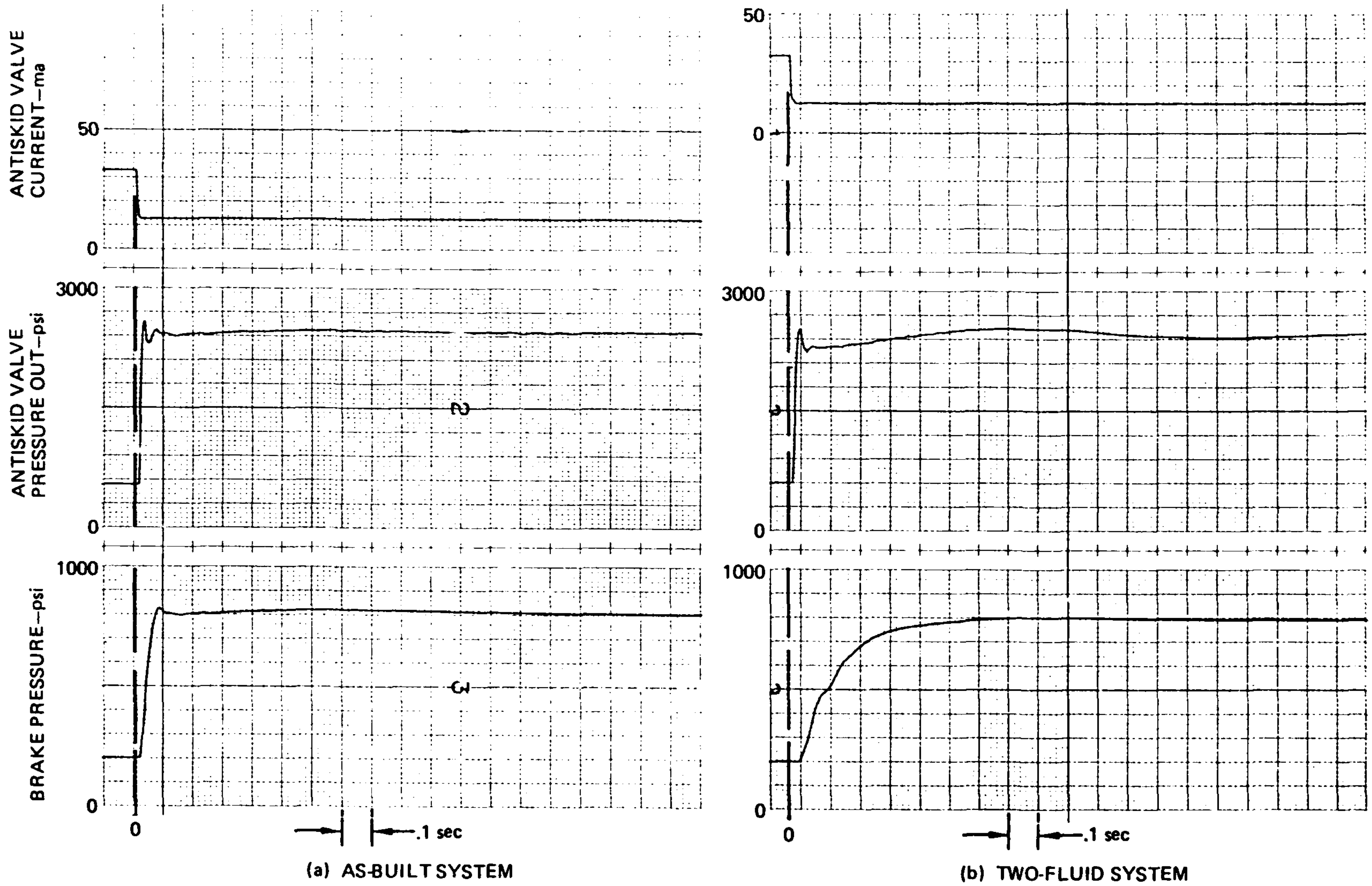


Figure D.52. System Response to Step Pressure Increase (20-80%) at -40^{o}F

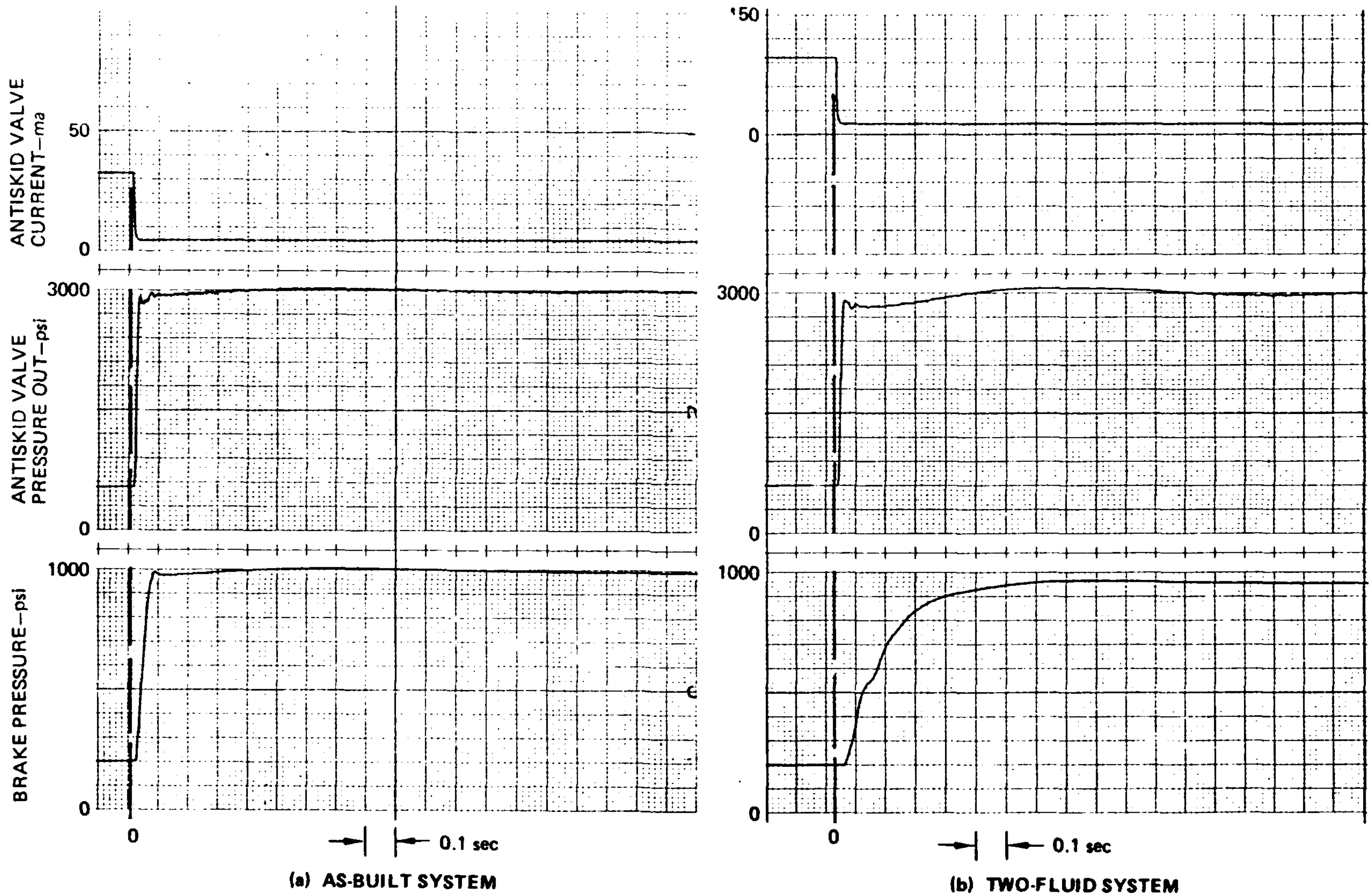


Figure D.53. System Response to Step Pressure Increase (20-100%) at -40°F

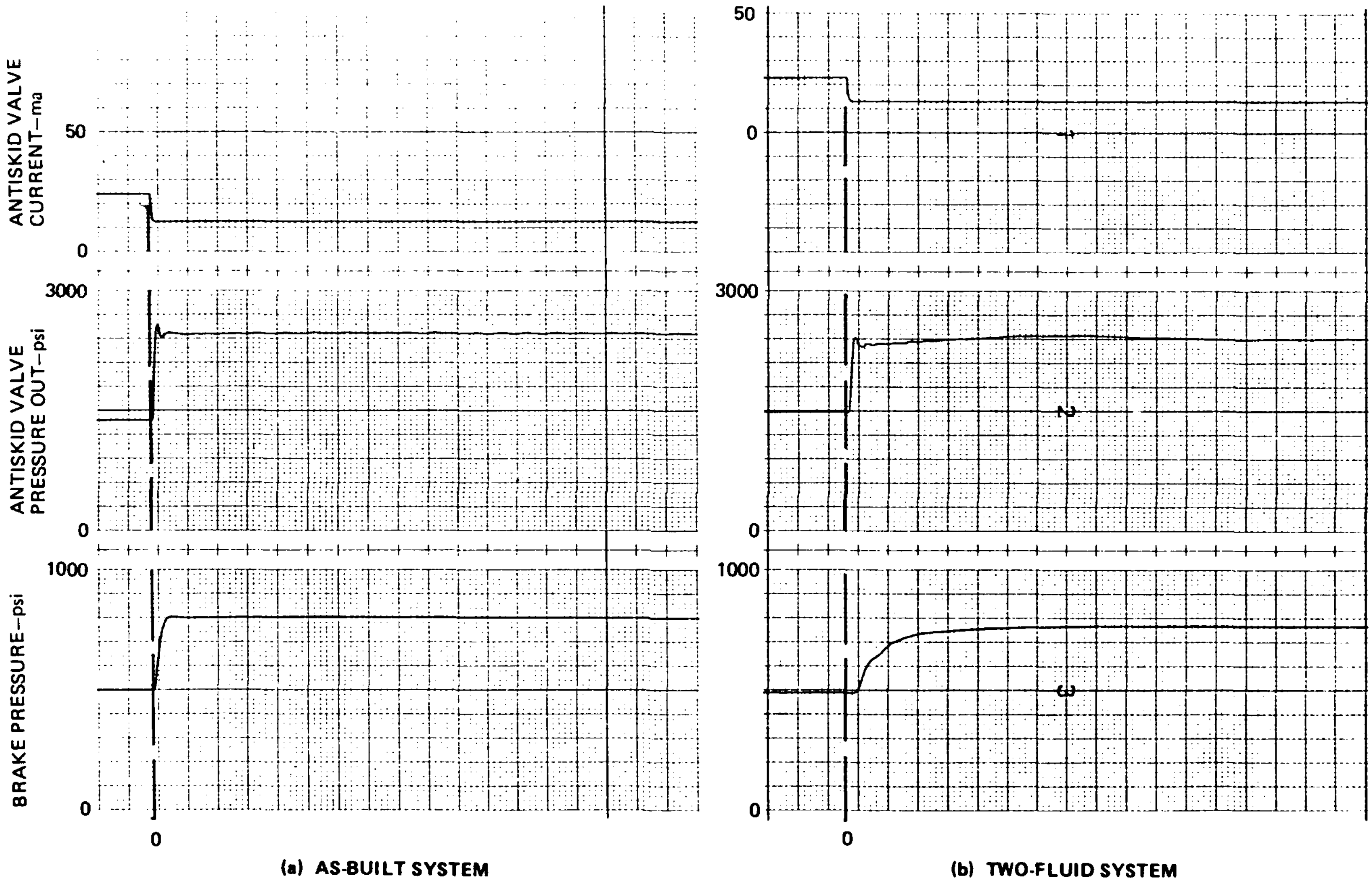


Figure D.54. System Response to Step·Pressure Increase (50-80%) at -40°F

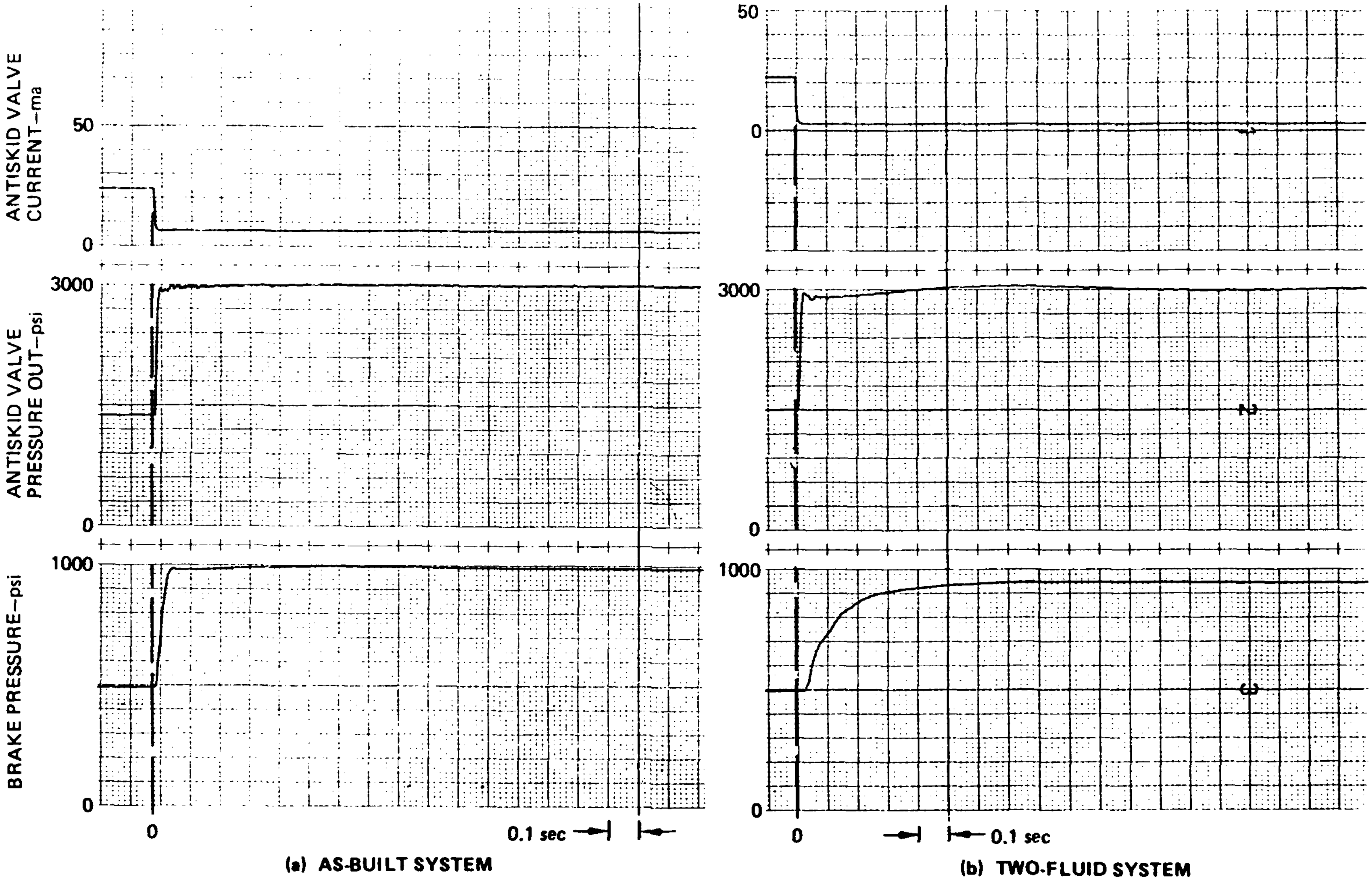


Figure D.55. System Response to Step Pressure Increase (50-100%) at -40°F

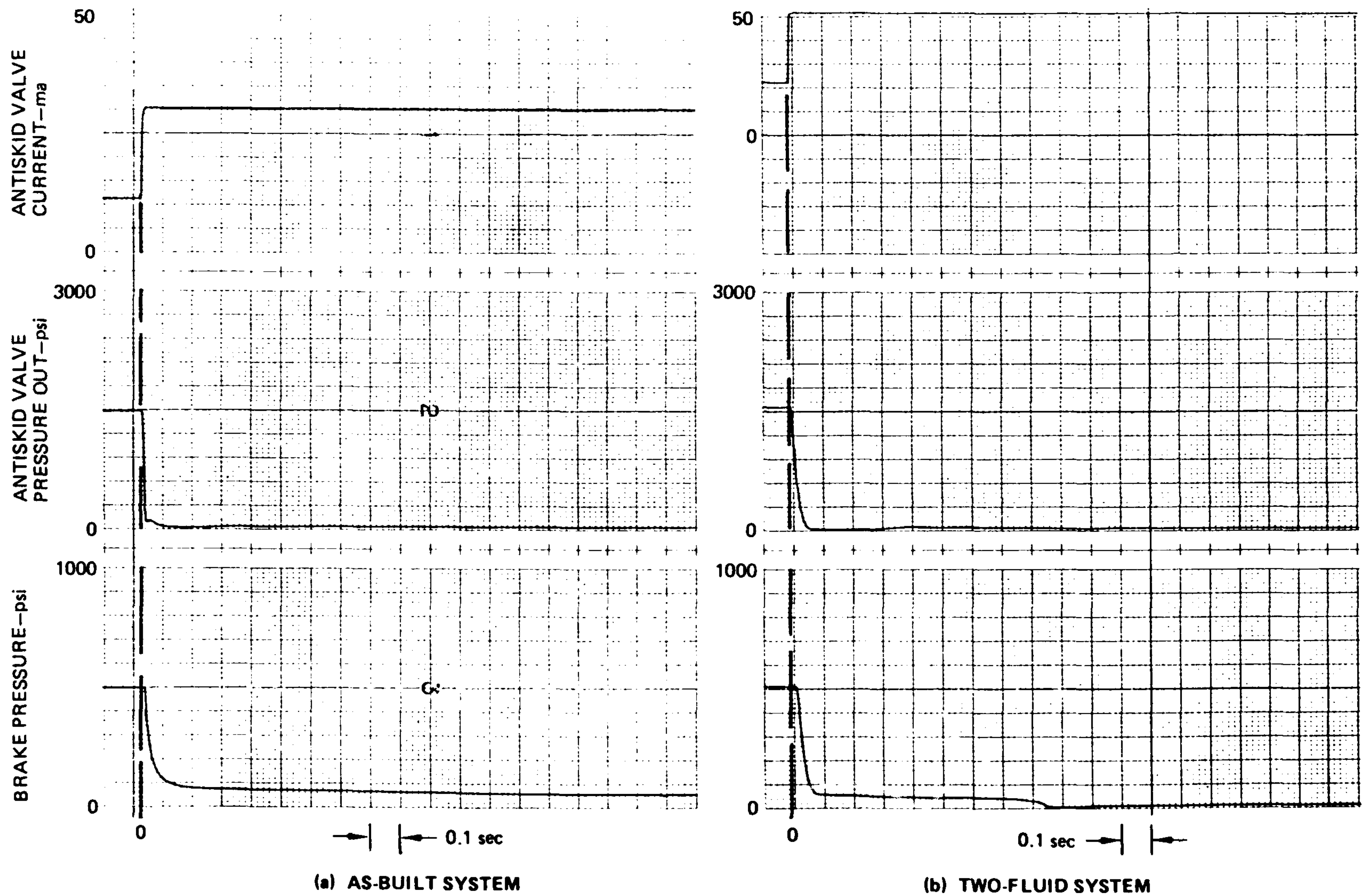


Figure D.56. System Response to Step Pressure Decrease (50-0%) at -40^{o}F

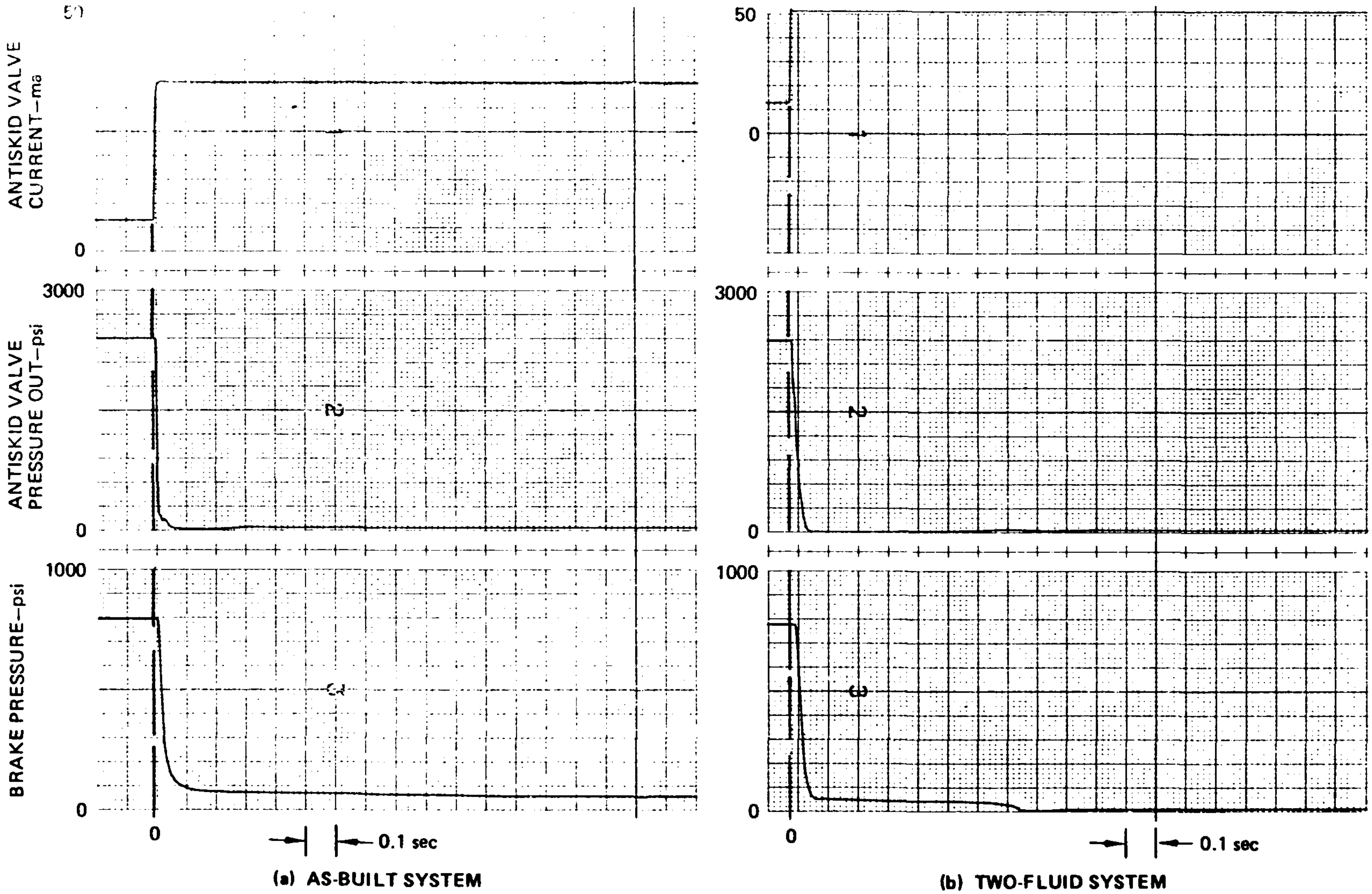


Figure D.57. System Response to Step Pressure Decrease (80-0%) at -40°F

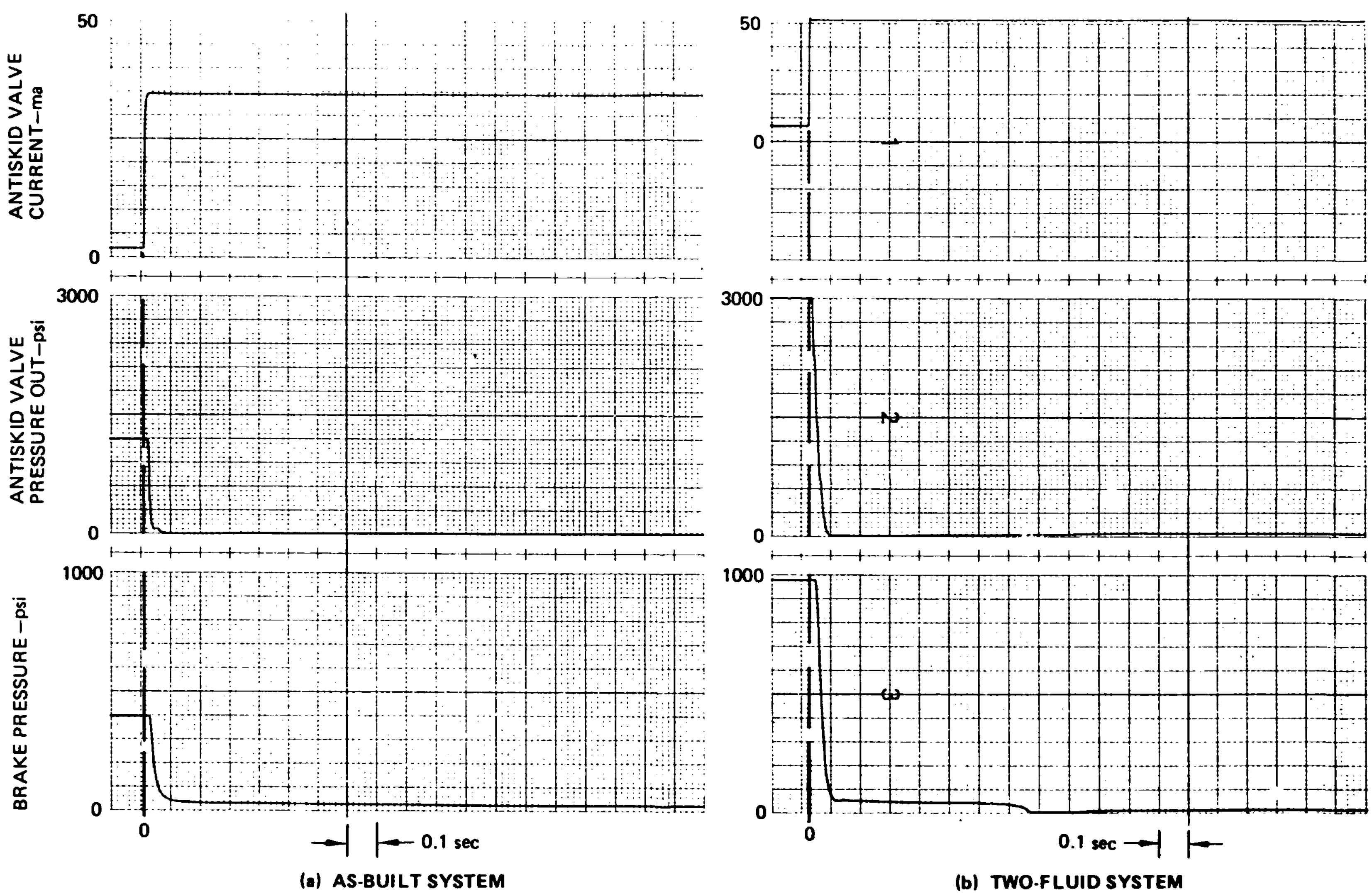


Figure D.58. System Response to Step Pressure Decrease (100-0%) at -40^{o}F

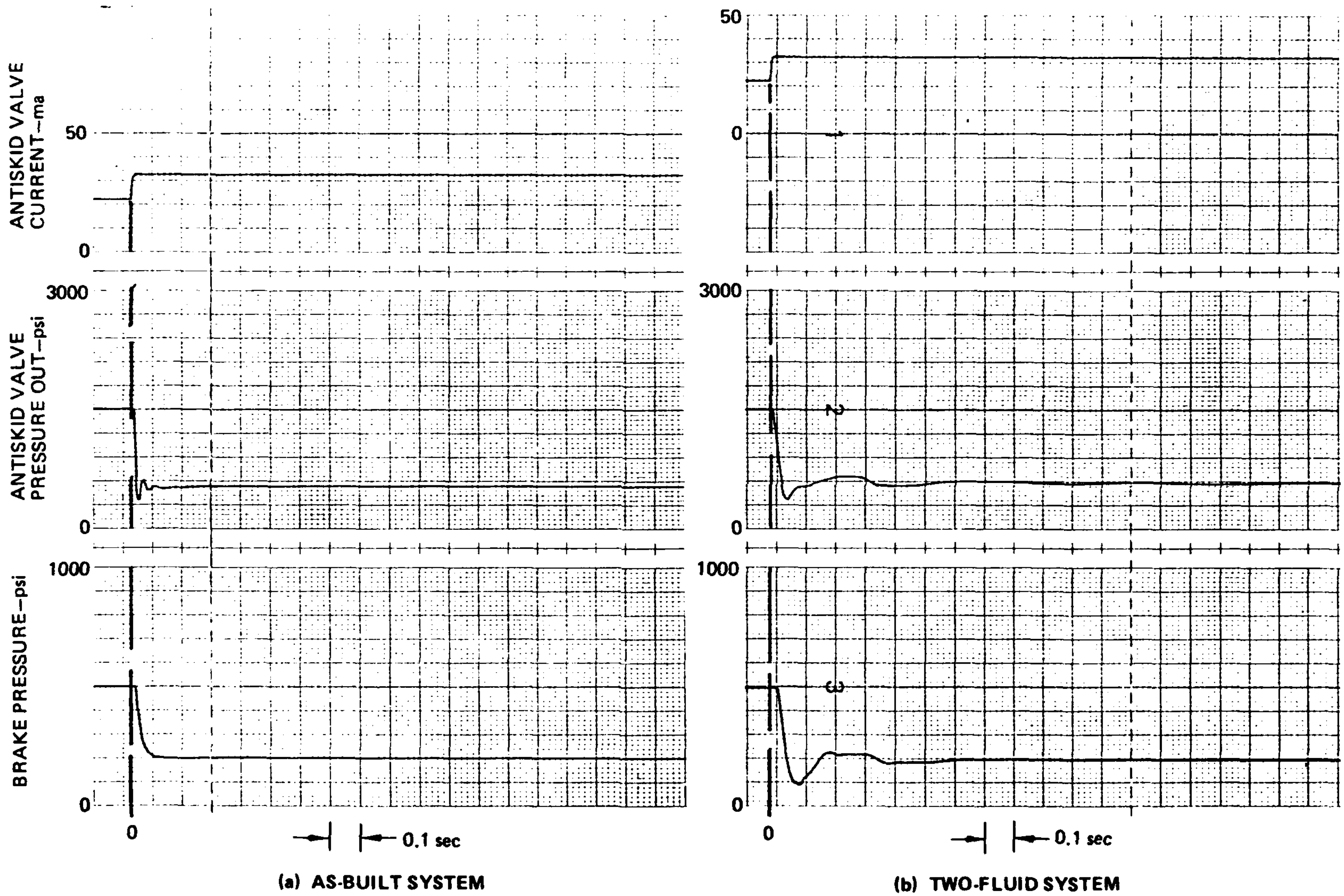


Figure D.59. System Response to Step Pressure Decrease (50-20%) at -40° F

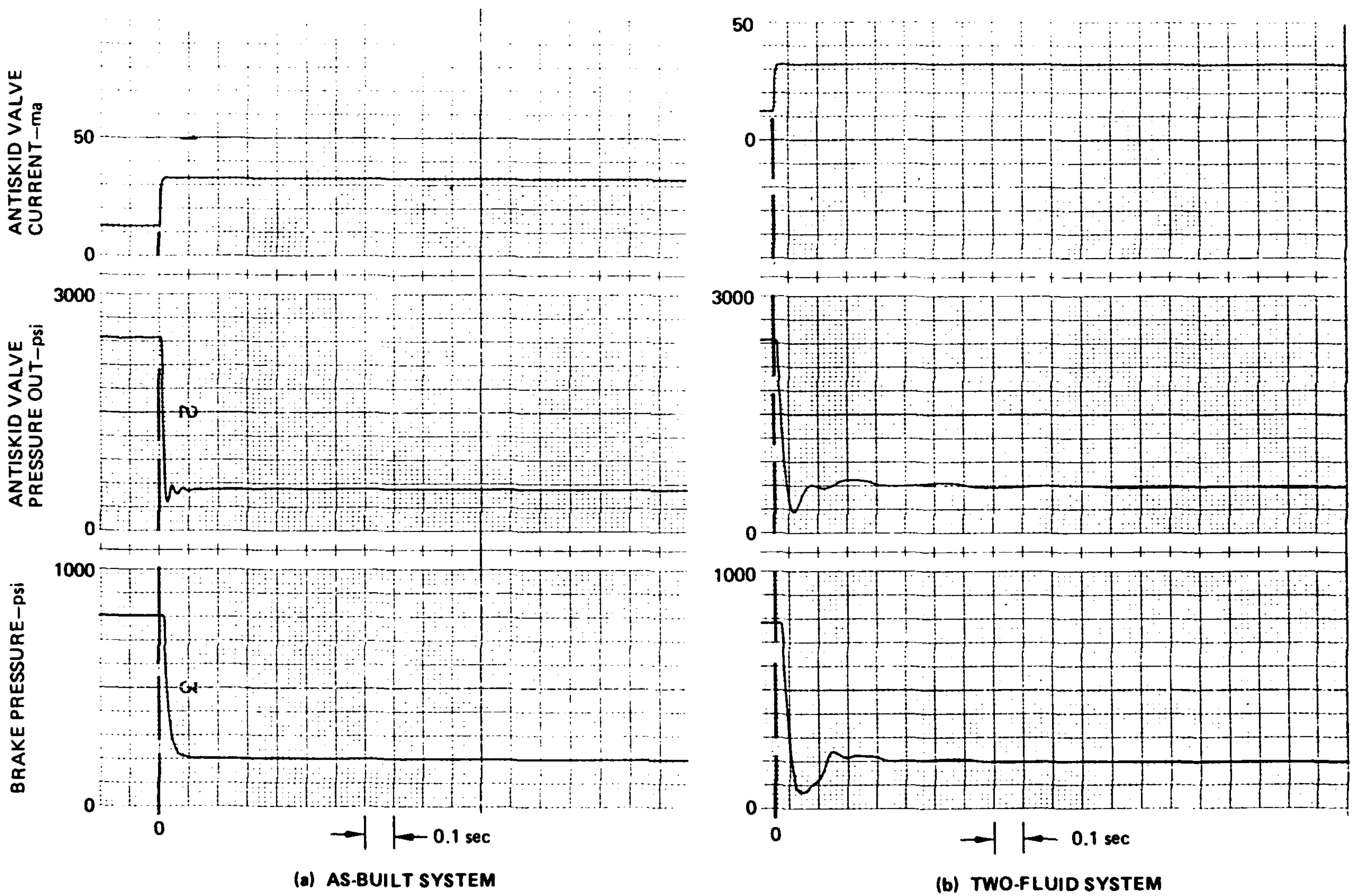
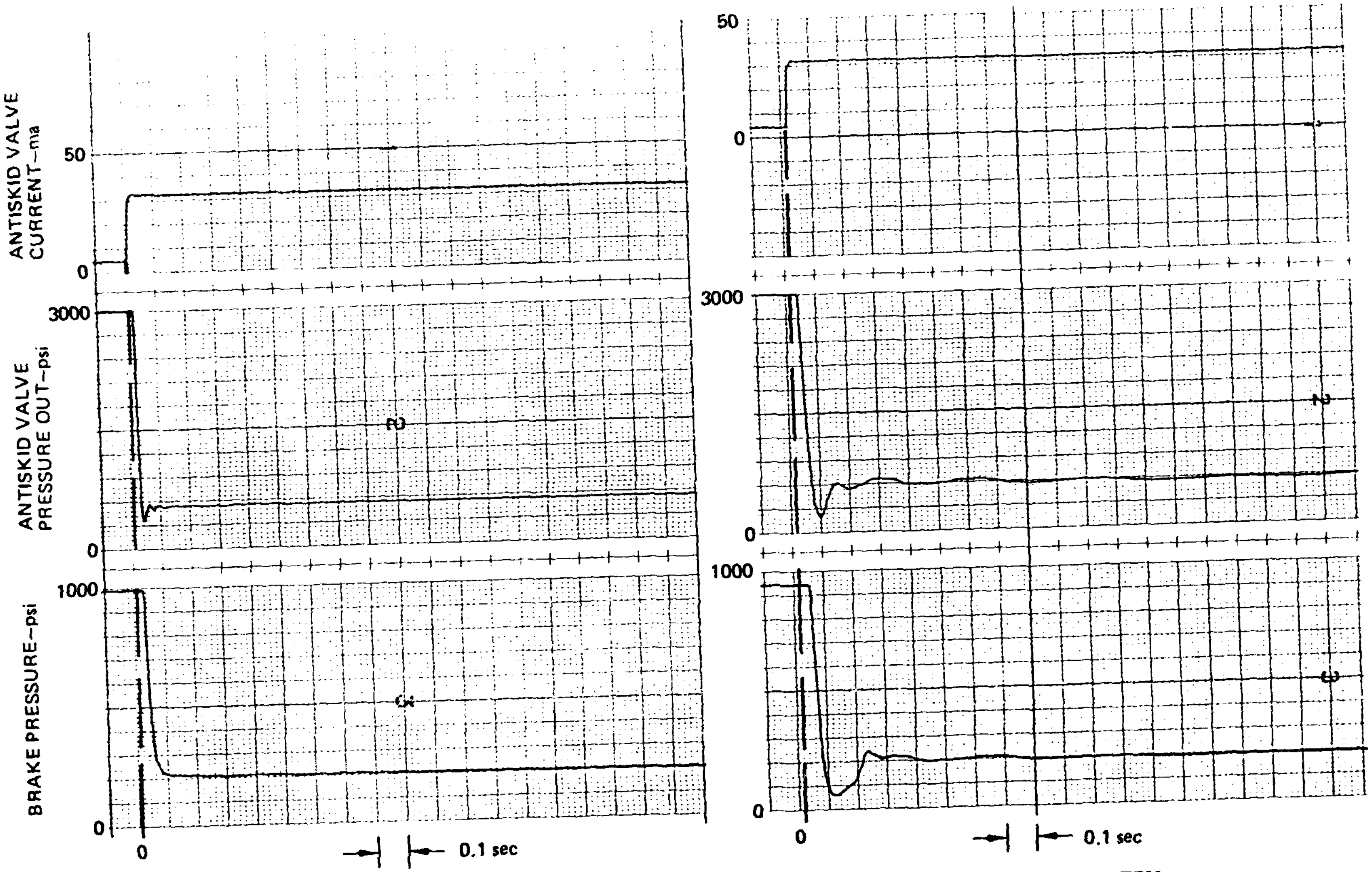


Figure D.60. System Response to Step Pressure Decrease (80-20%) at -40°F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.61. System Response to Step Pressure Decrease (100-20%) at -40°F

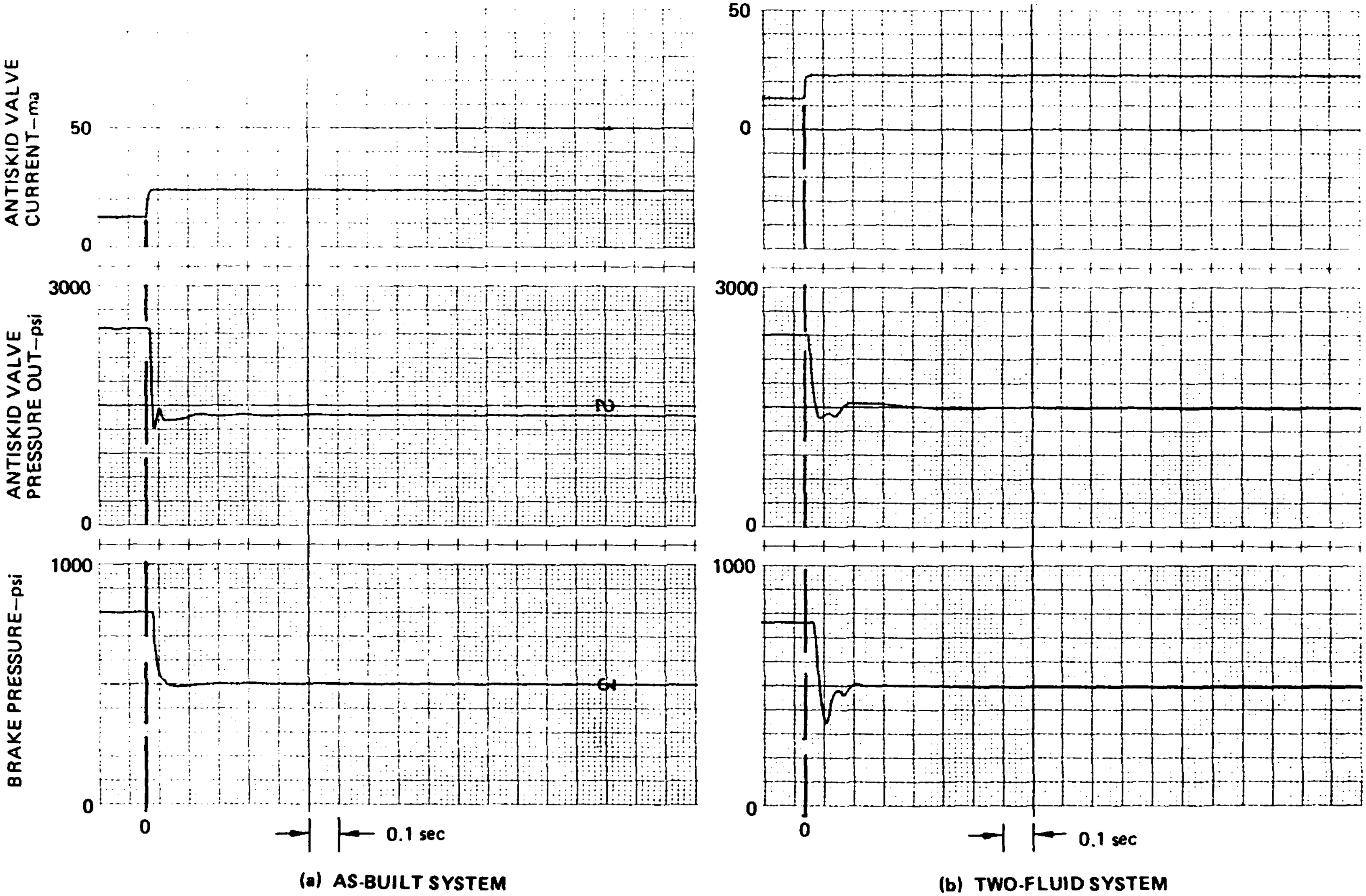


Figure D.62. System Response to Step Pressure Decrease (80-50%) at -40° F

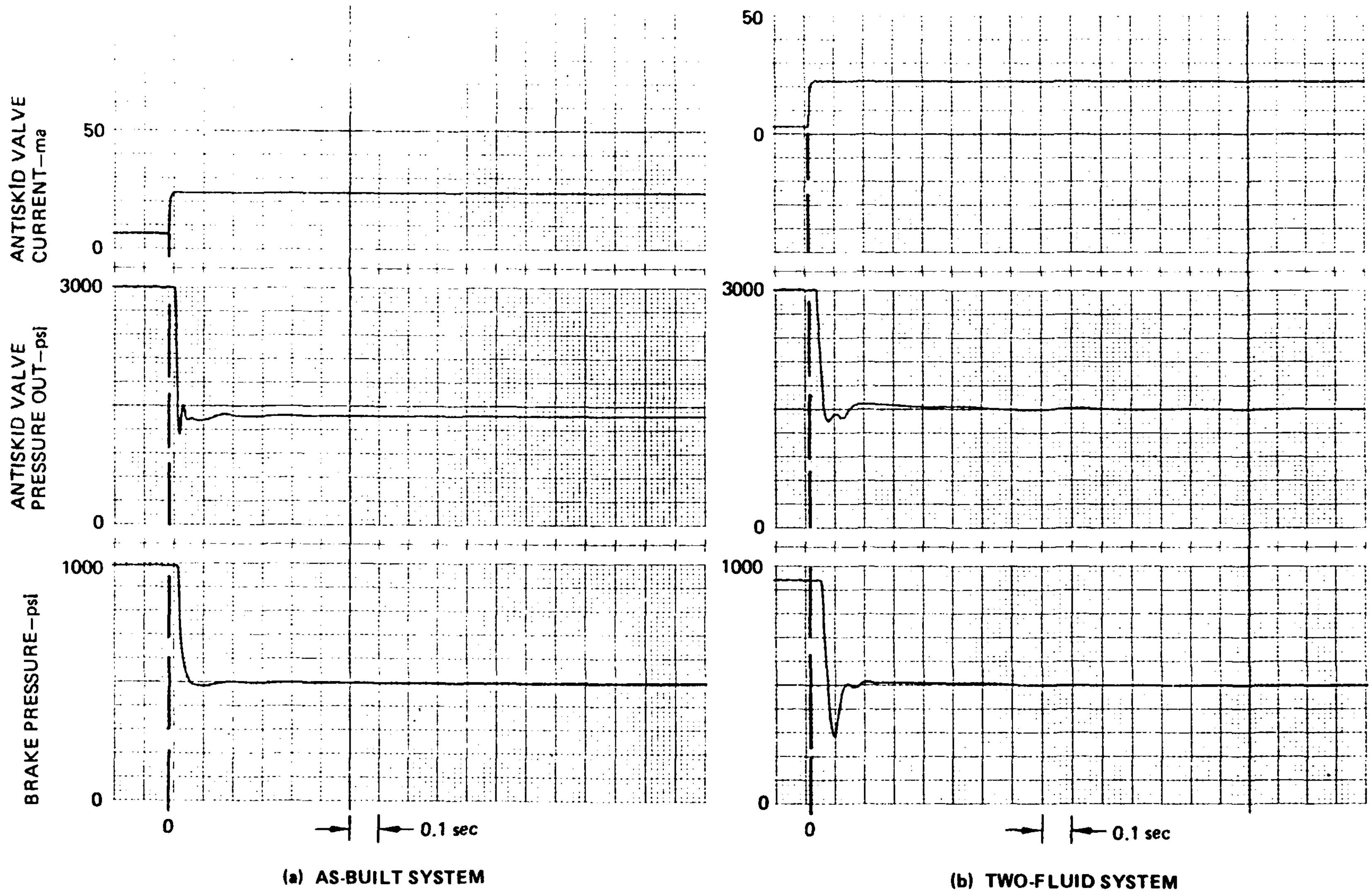


Figure D.63. System Response to Step Pressure Decrease (100-50%) at -40° F

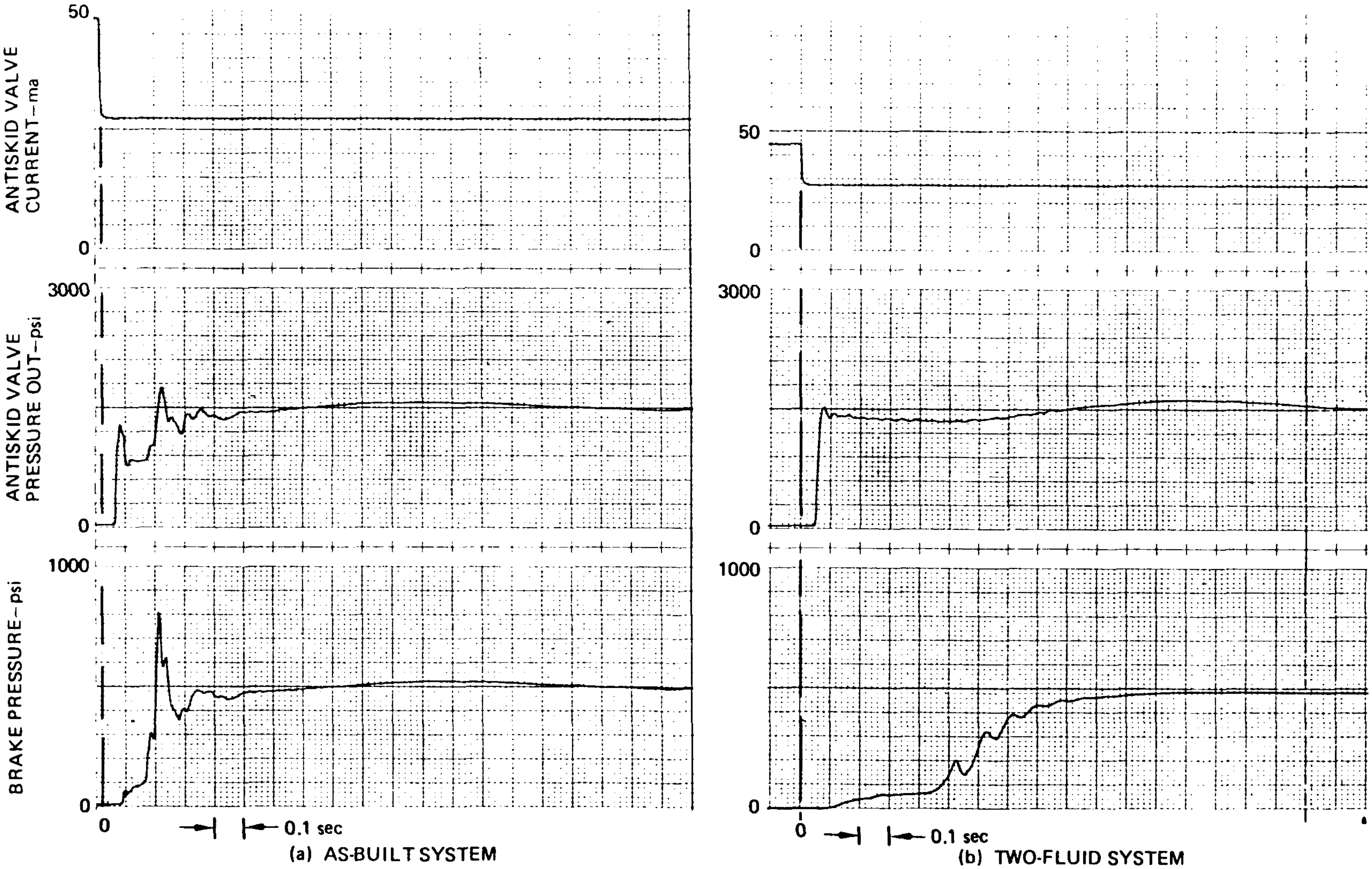


Figure D.64. System Response to Step Pressure Increase (0-50%) at 160°F

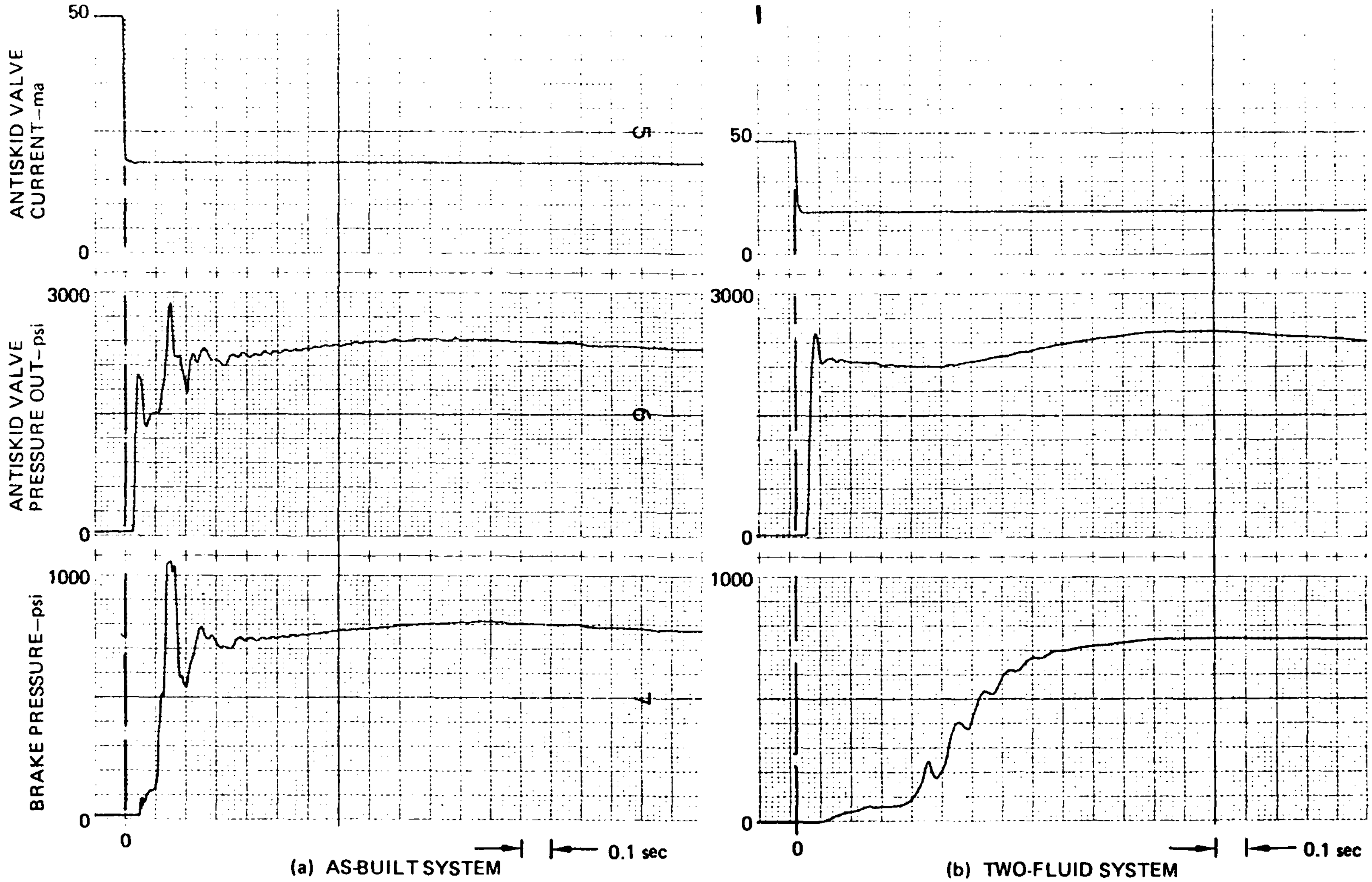
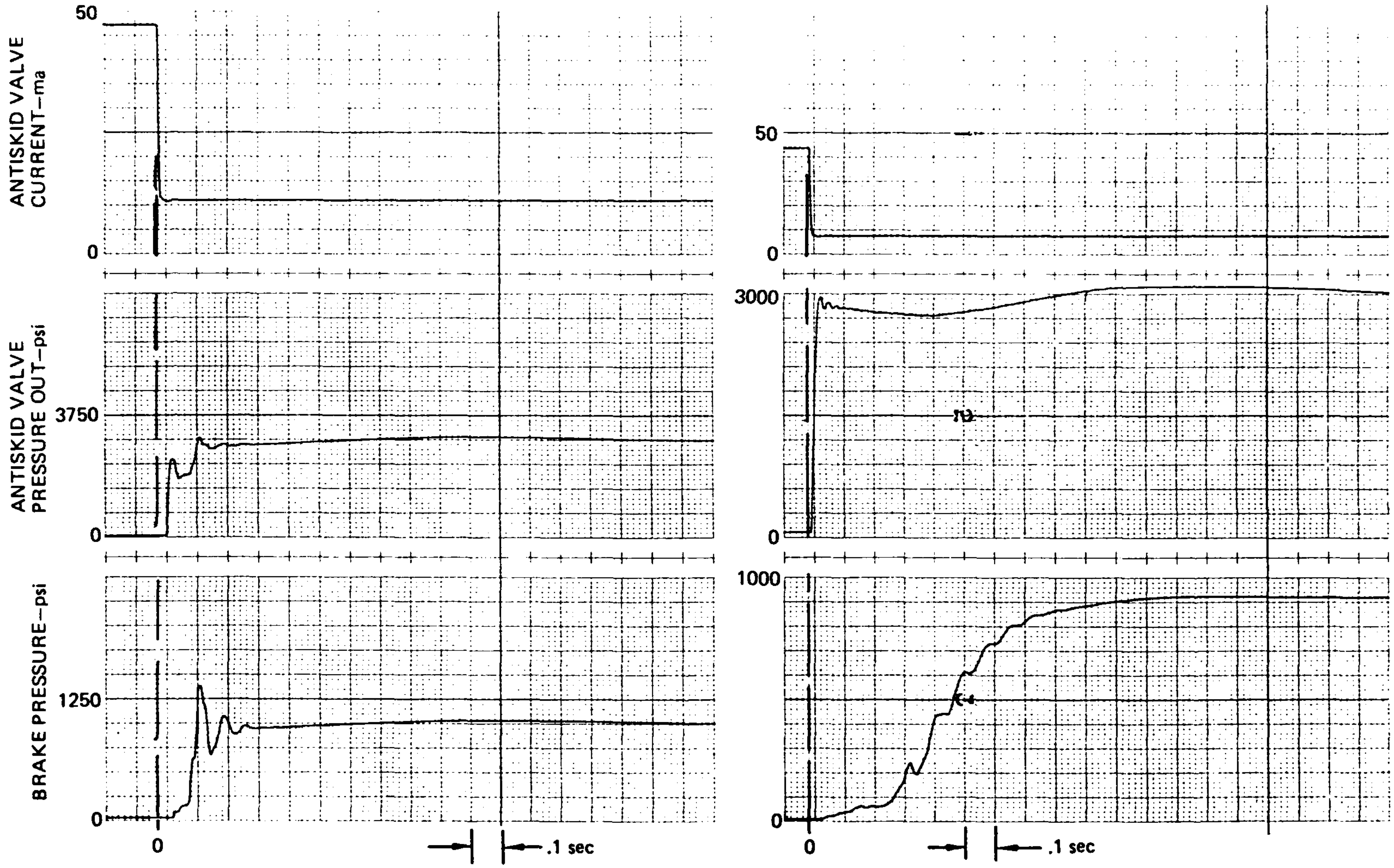


Figure D.65. System Response to Step Pressure Increase (0-80%) at 160°F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.66. System Response to Step Pressure Increase (0-100%) at 160^{o}F

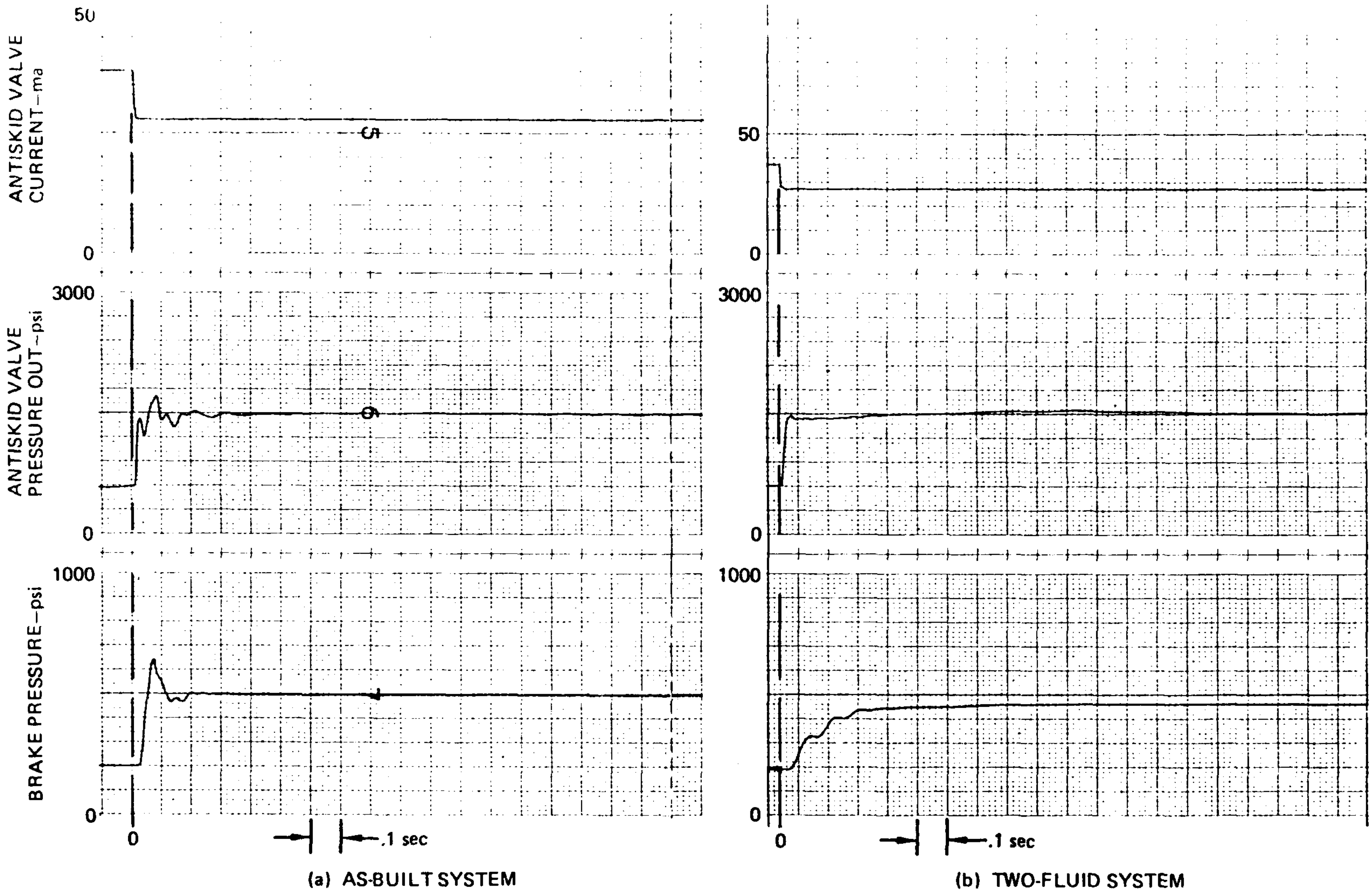


Figure D.67. System Response to Step Pressure Increase (20-50%) at 160^{o}F

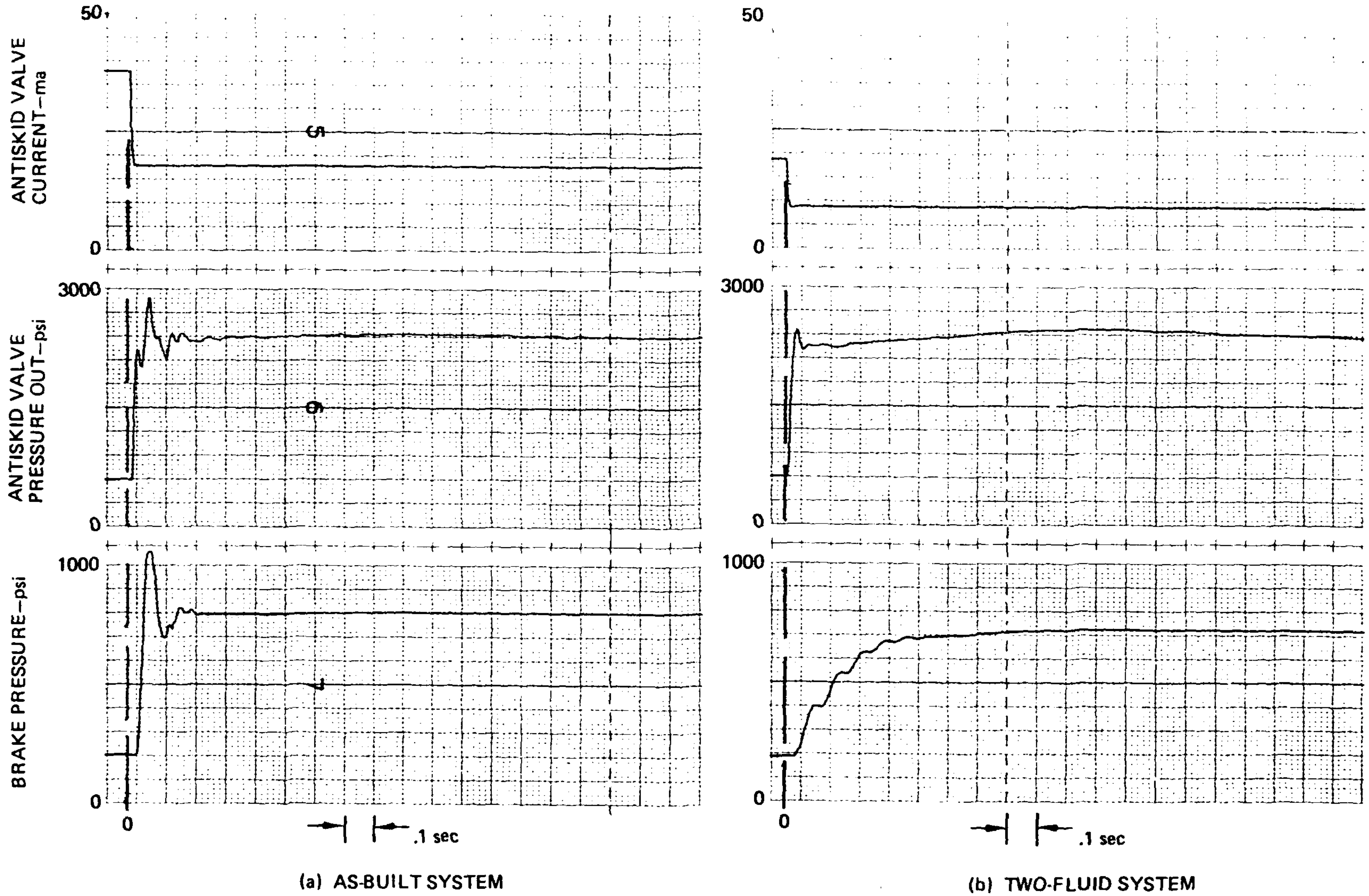
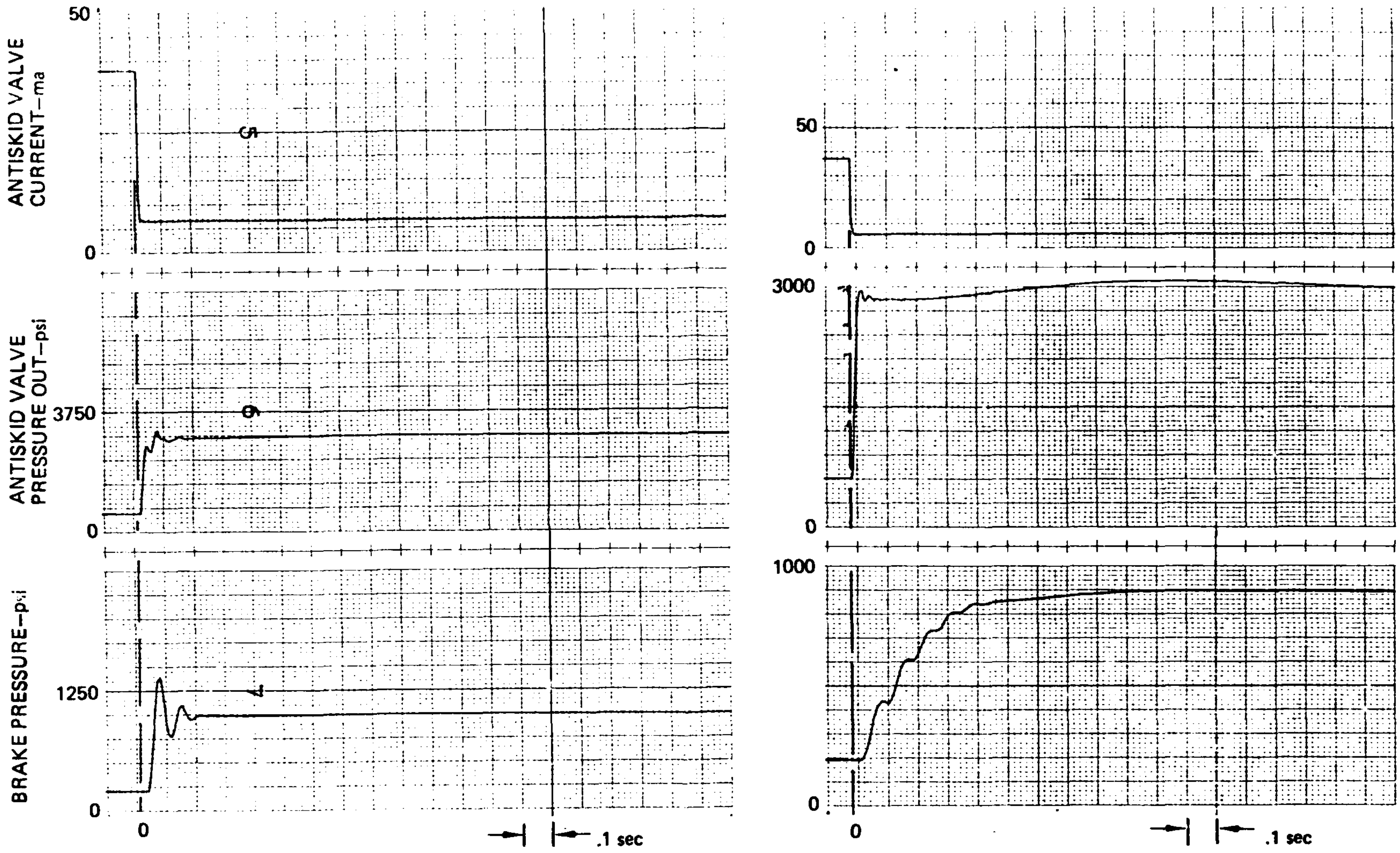


Figure D.68. System Response to Step Pressure Increase (20-80%) at 160° F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.69. System Response to Step Pressure Increase (20-100%) at 160^{0}F

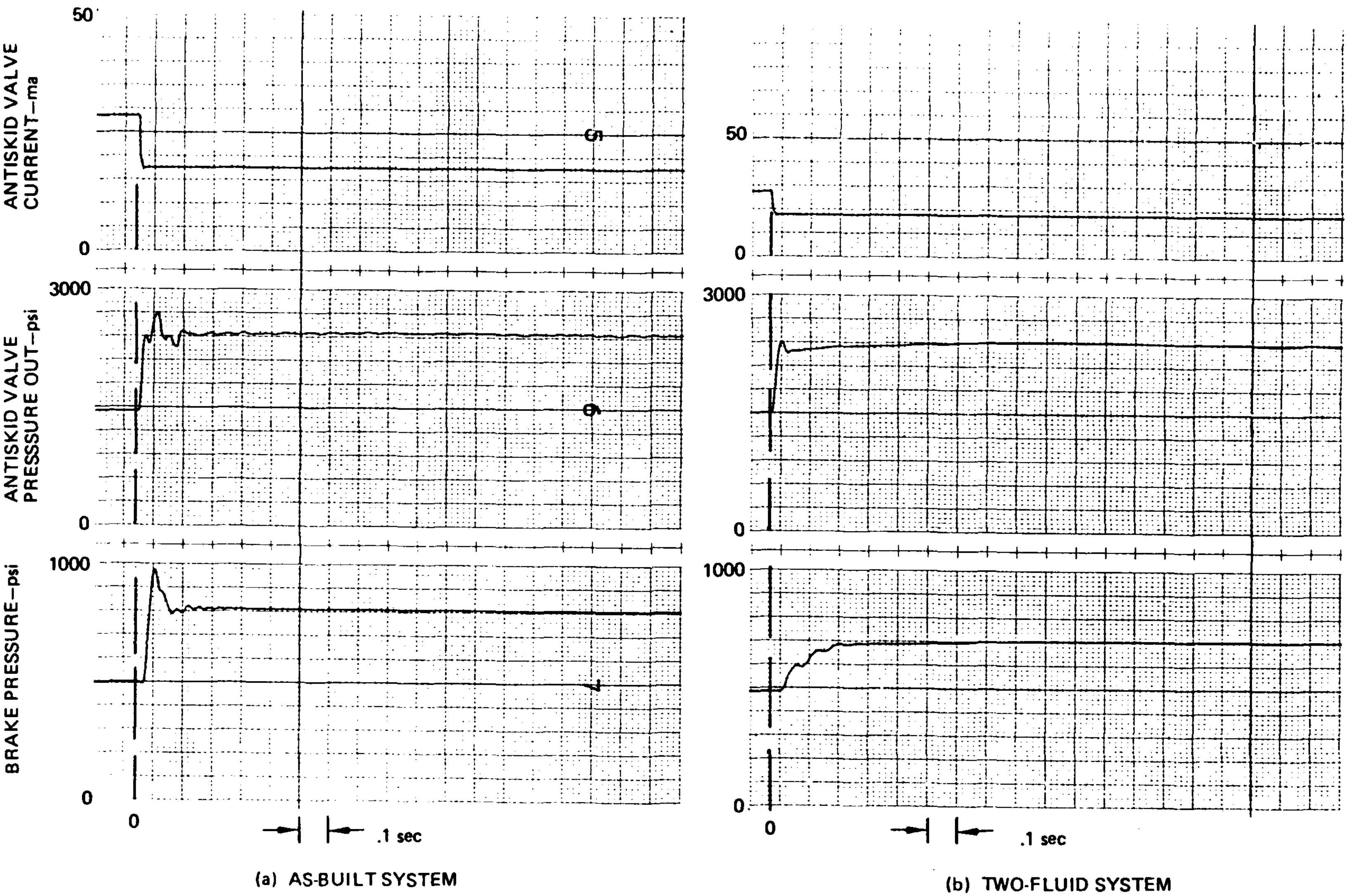


Figure D.70. System Response to Step Pressure Increase (50-80%) at 160^{o}F

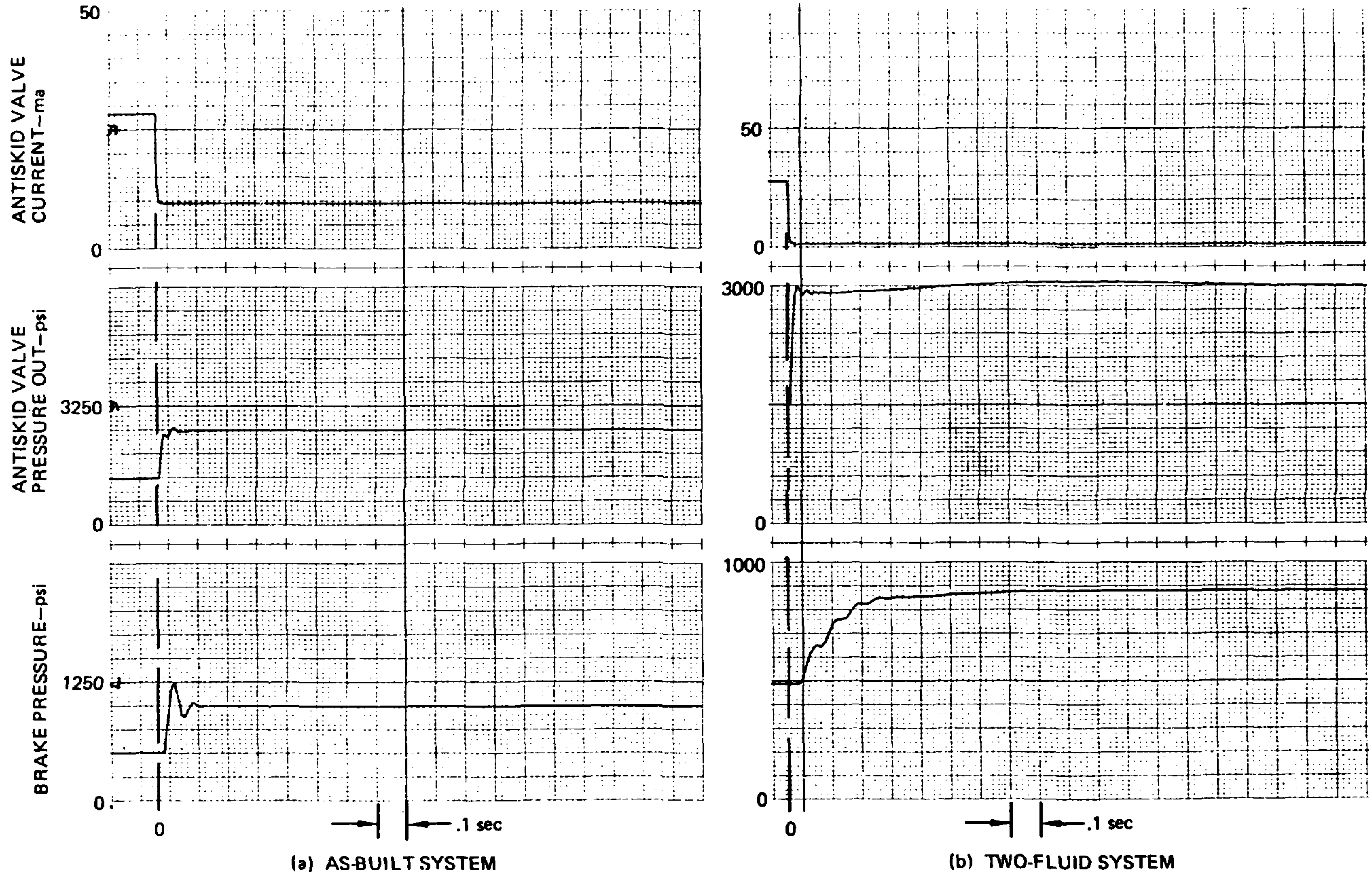


Figure D.71. System Response to Step Pressure Increase (50-100%) at 160°F

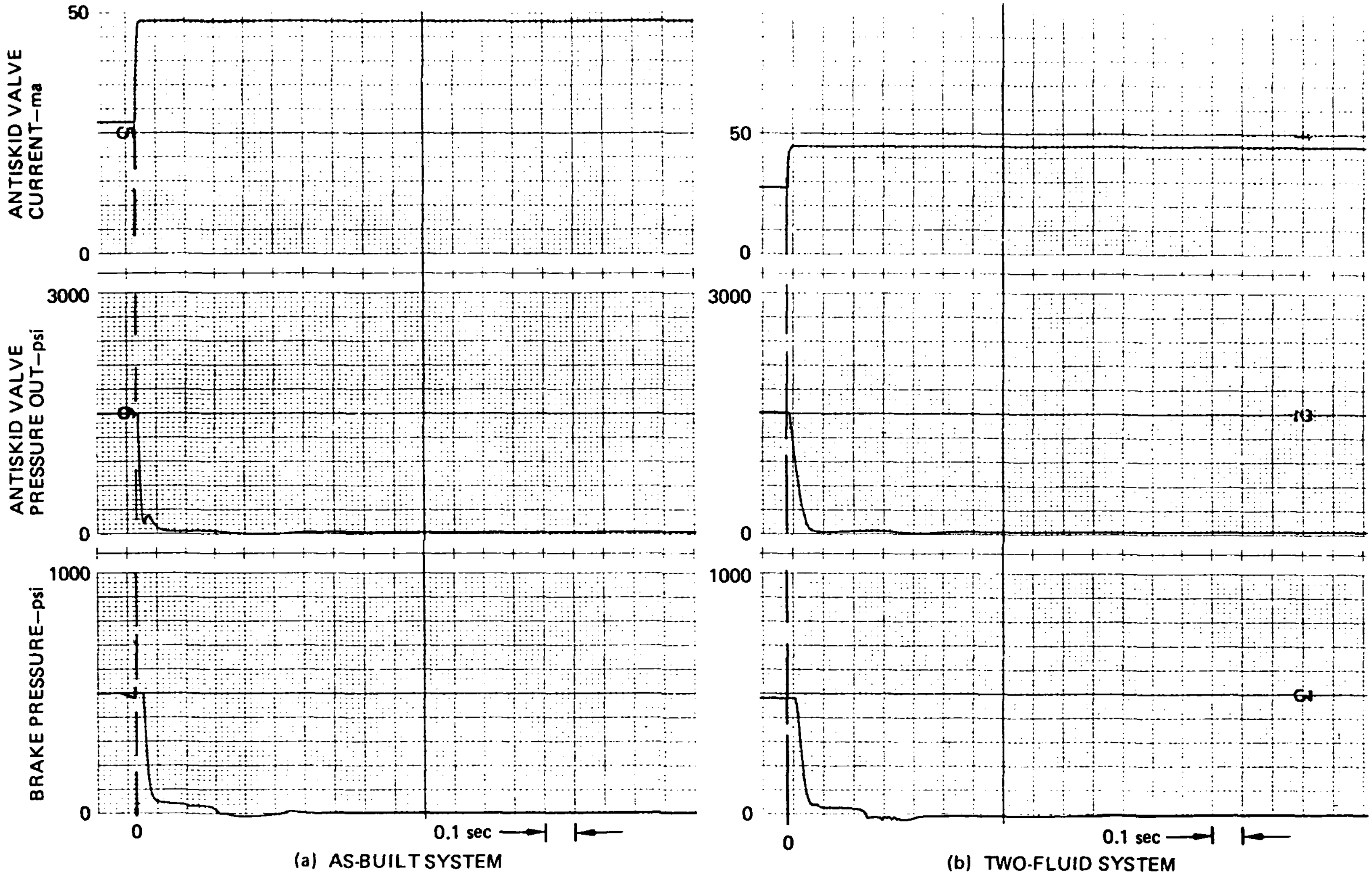


Figure D.72. System Response to Step Pressure Decrease (50-0%) at 160^{o}F

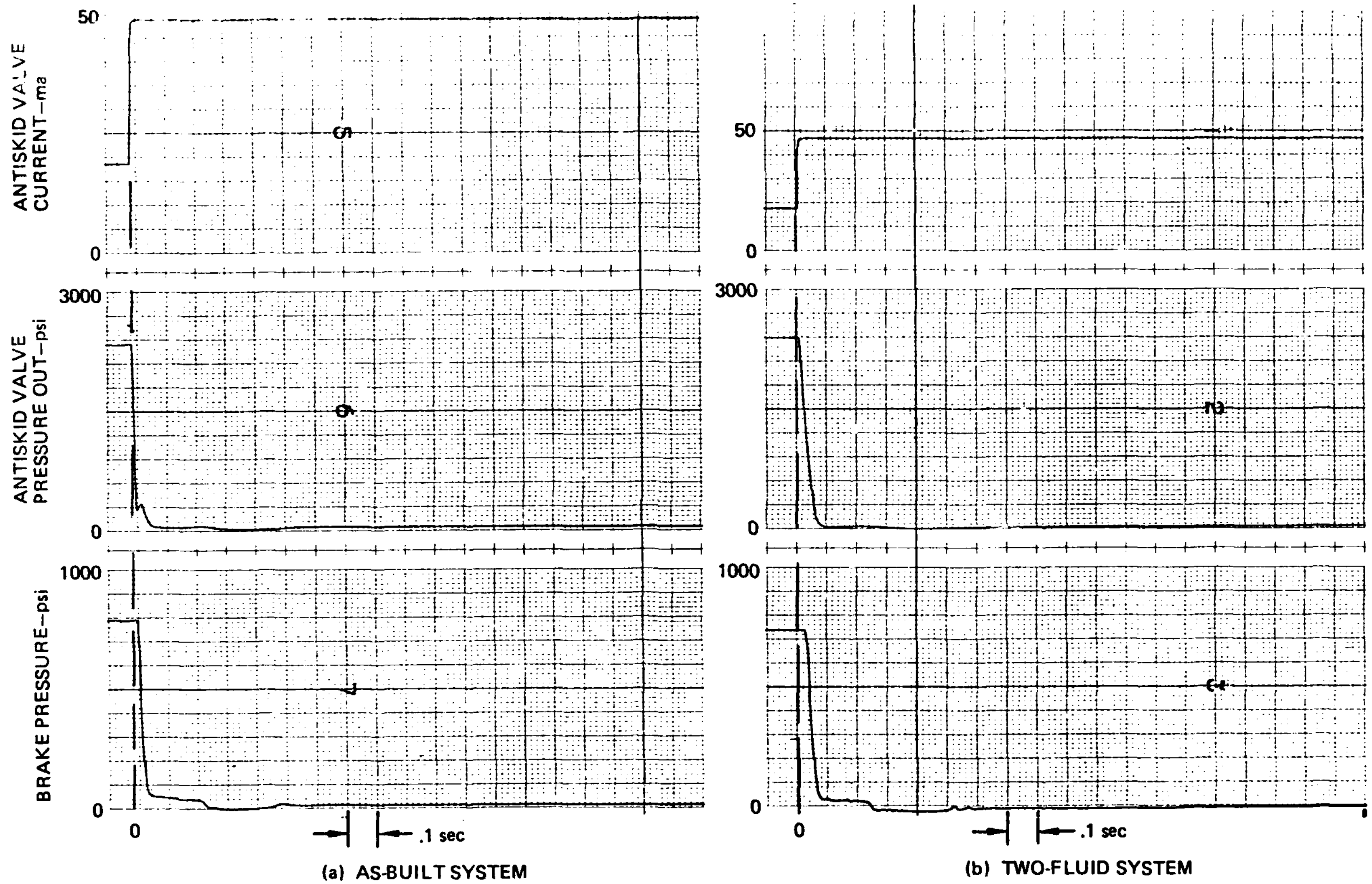


Figure D.73. System Response to Step Pressure Decrease (80-0%) at 160^{o}F

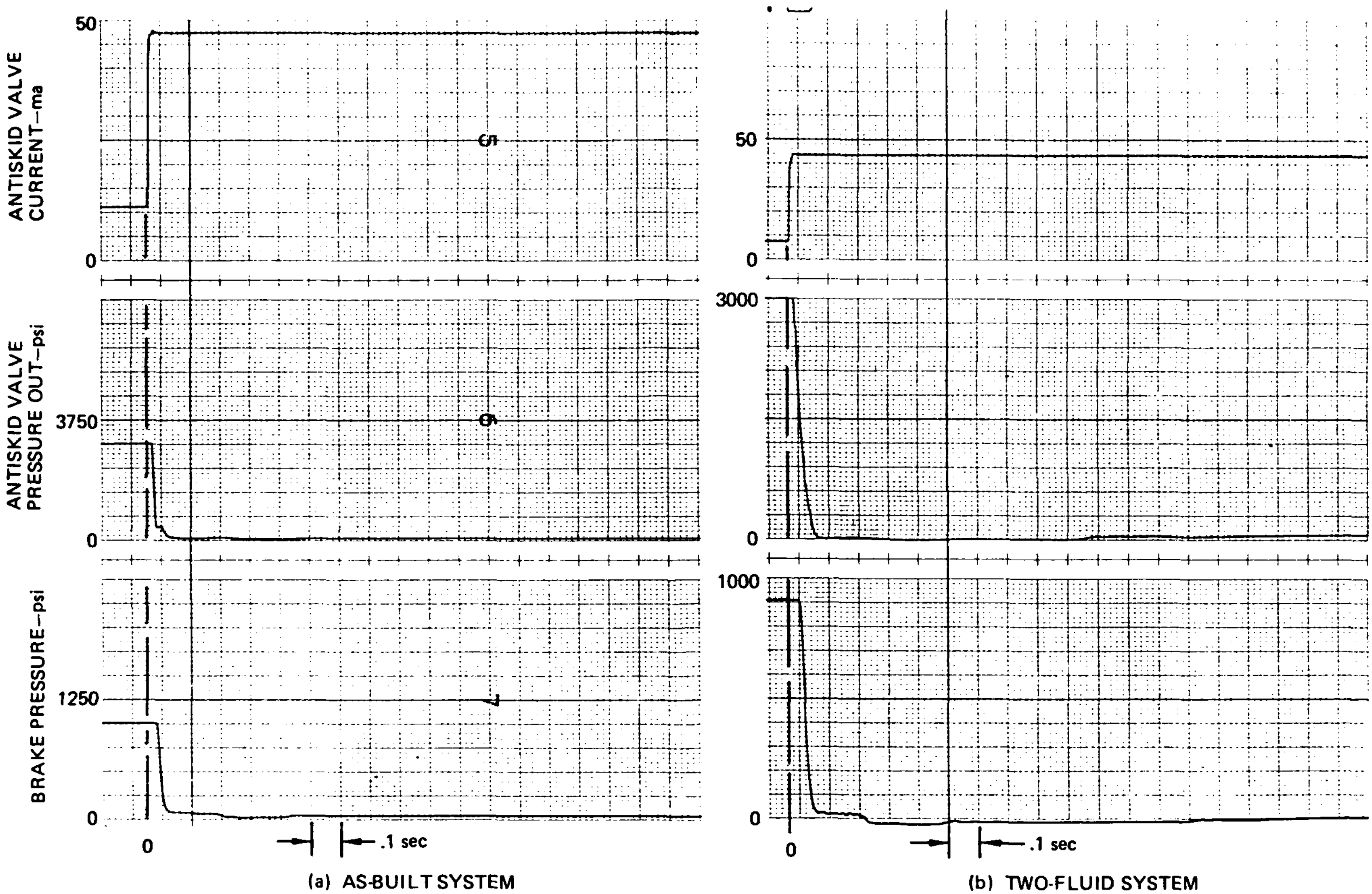
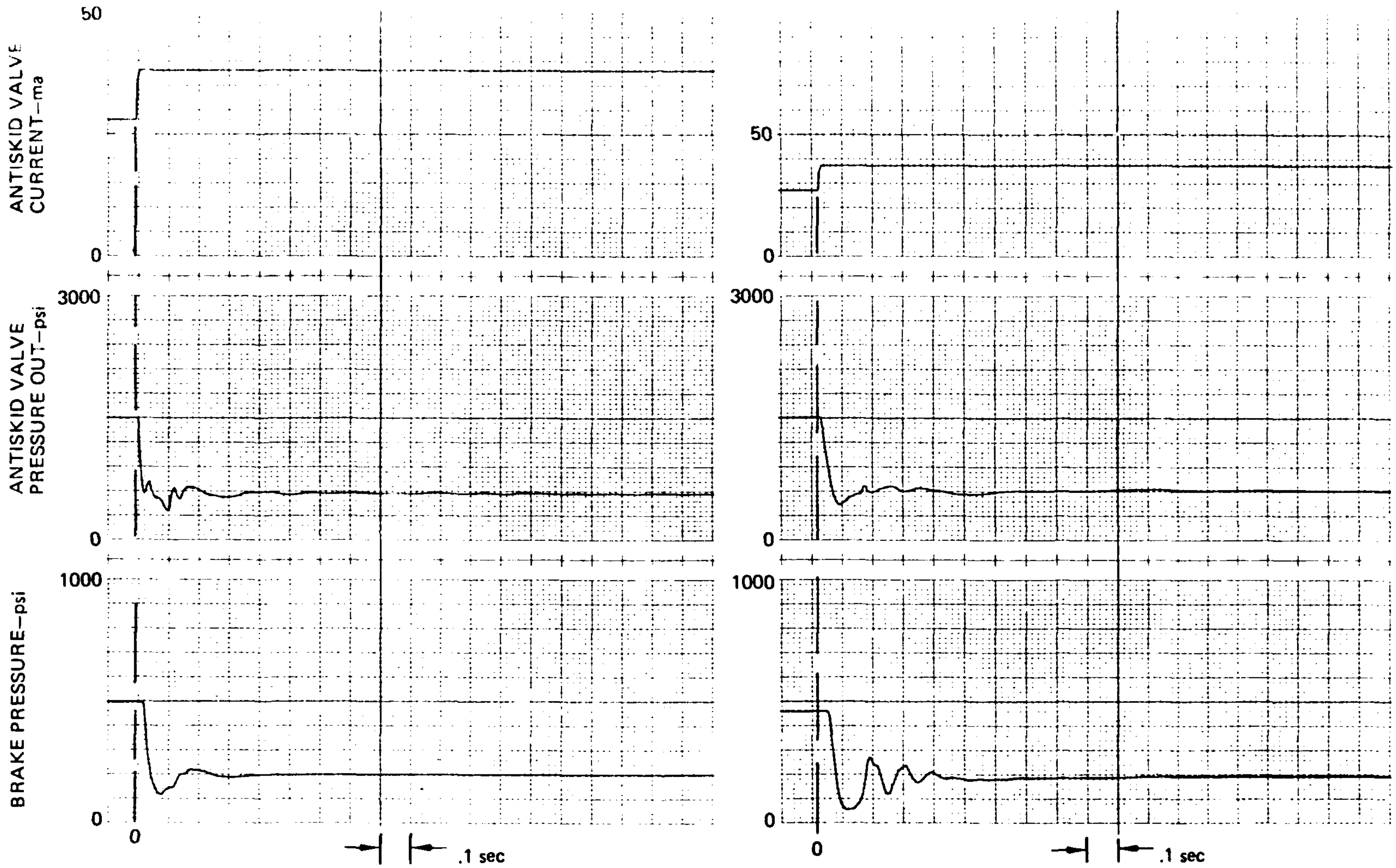


Figure D.74. System Response to Step Pressure Decrease (100-0%) at 160°F



(a) AS-BUILT SYSTEM

(b) TWO-FLUID SYSTEM

Figure D.75. System Response to Step Pressure Decrease (50-20%) at 160°F

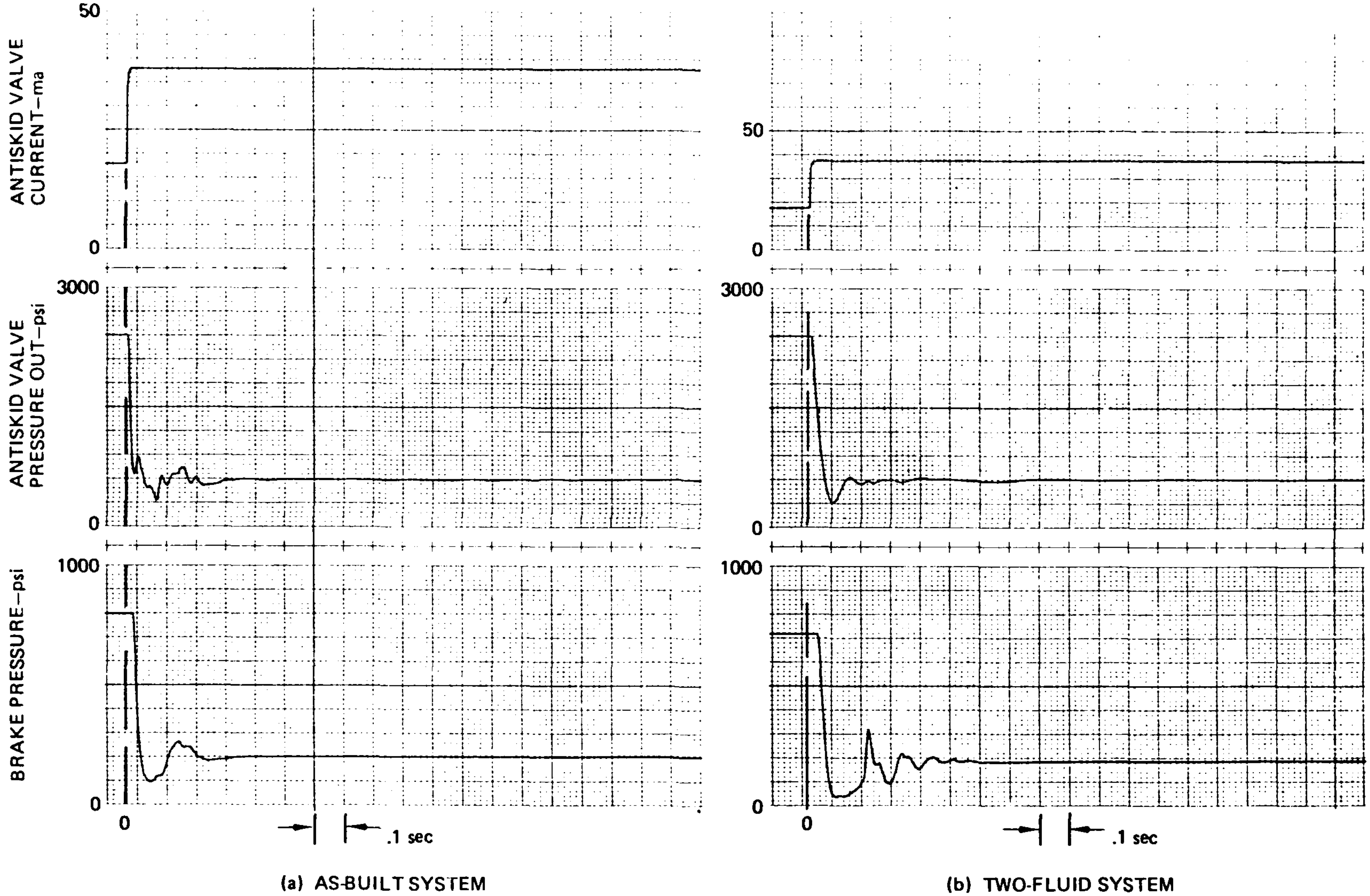


Figure D.76. System Response to Step Pressure Decrease (80-20%) at 160° F

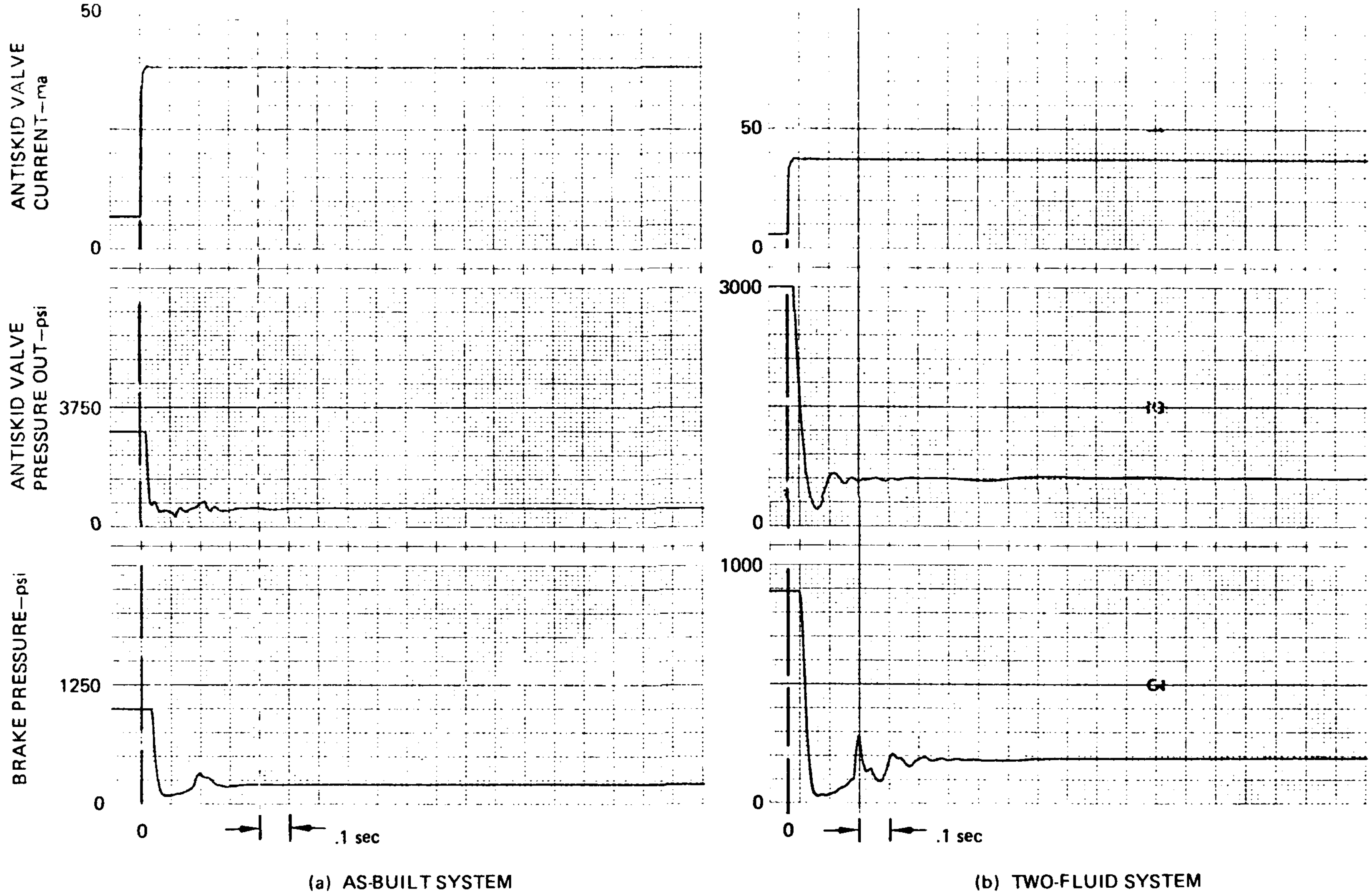


Figure D.77. System Response to Step Pressure Decrease (100-20%) at 160^{o}F

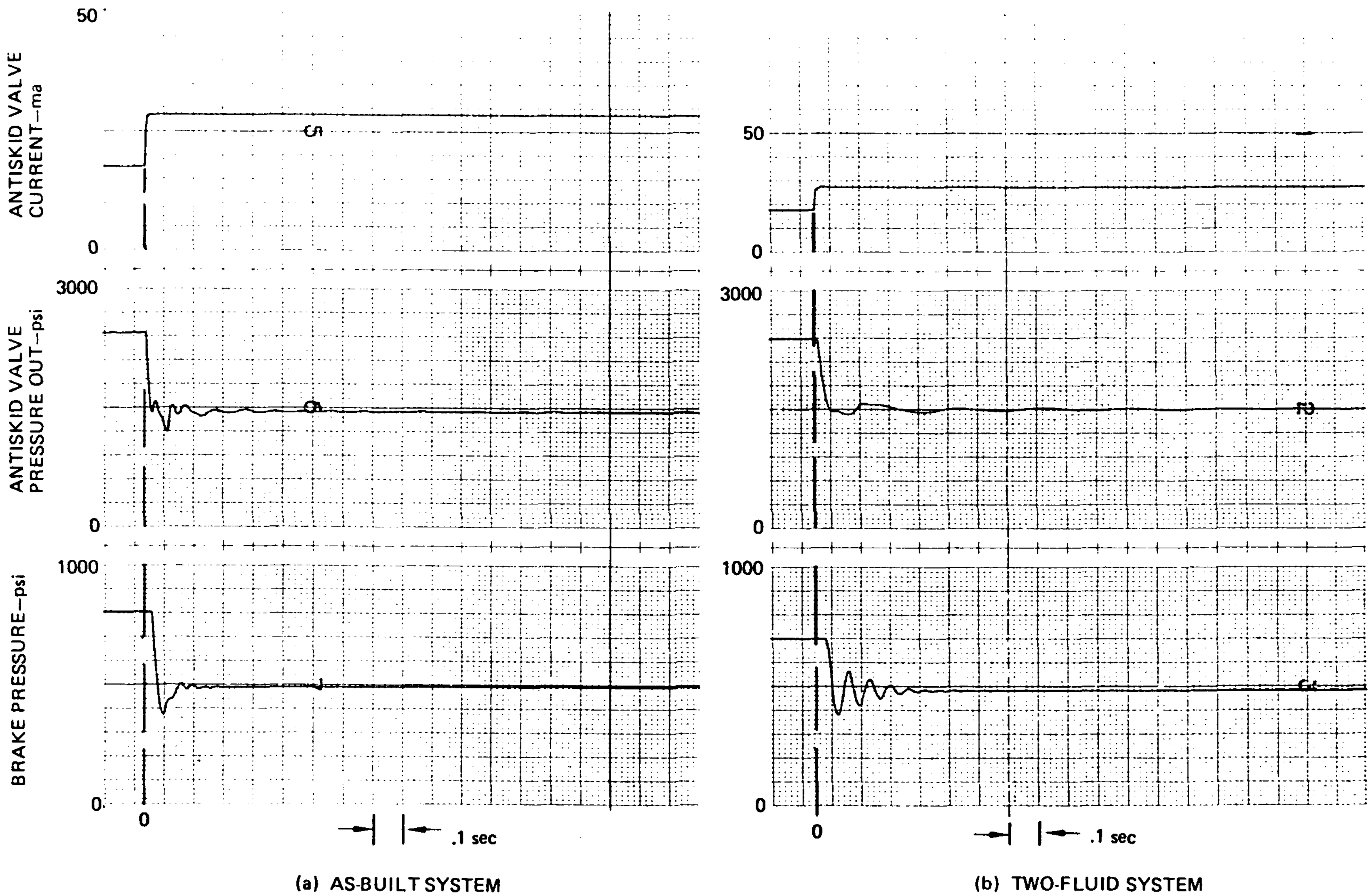


Figure D.78. System Response to Step Pressure Decrease (80-50%) at 160^{o}F

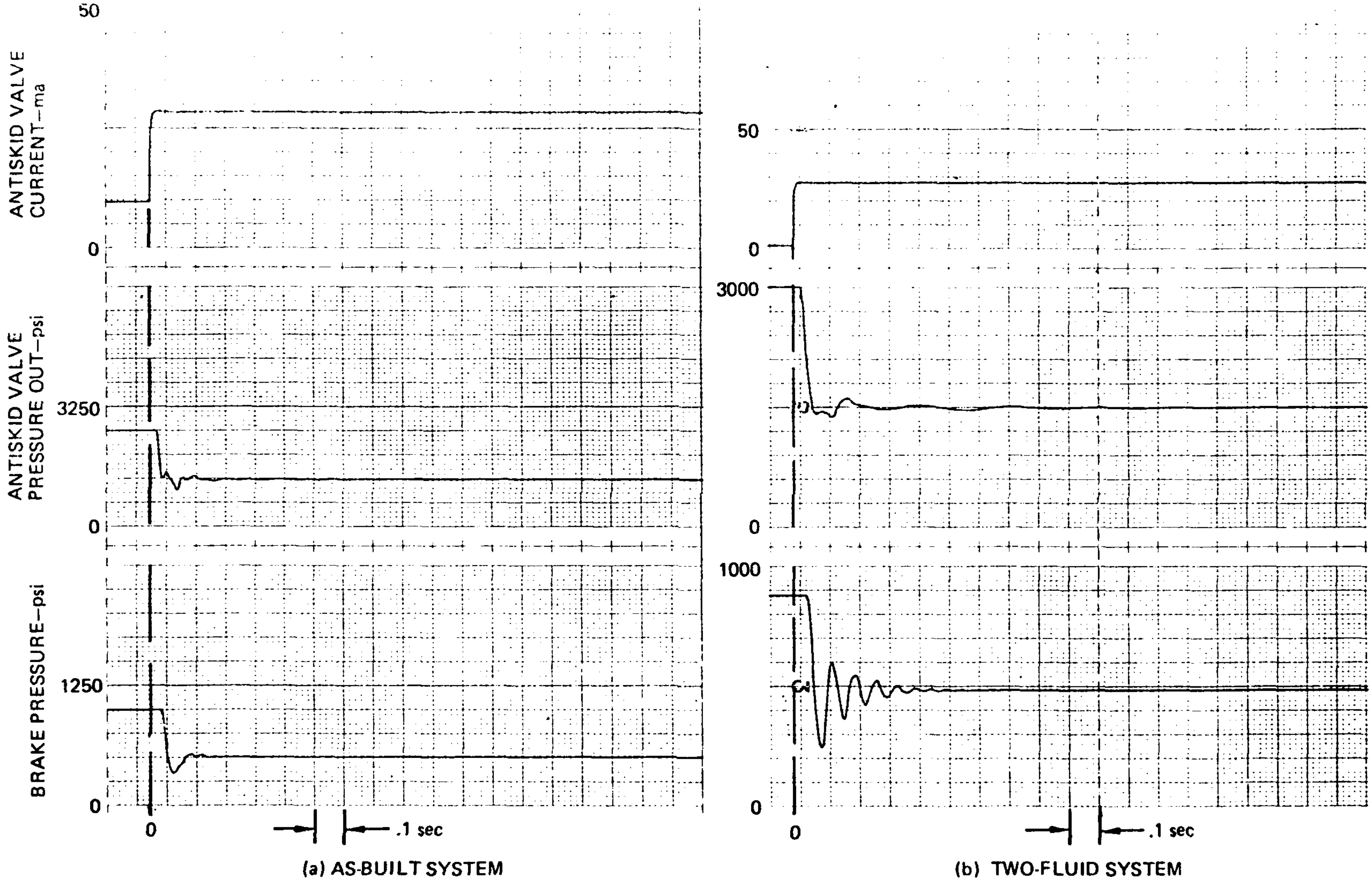


Figure D.79. System Response to Step Pressure Decrease (100-50%) at 160°F

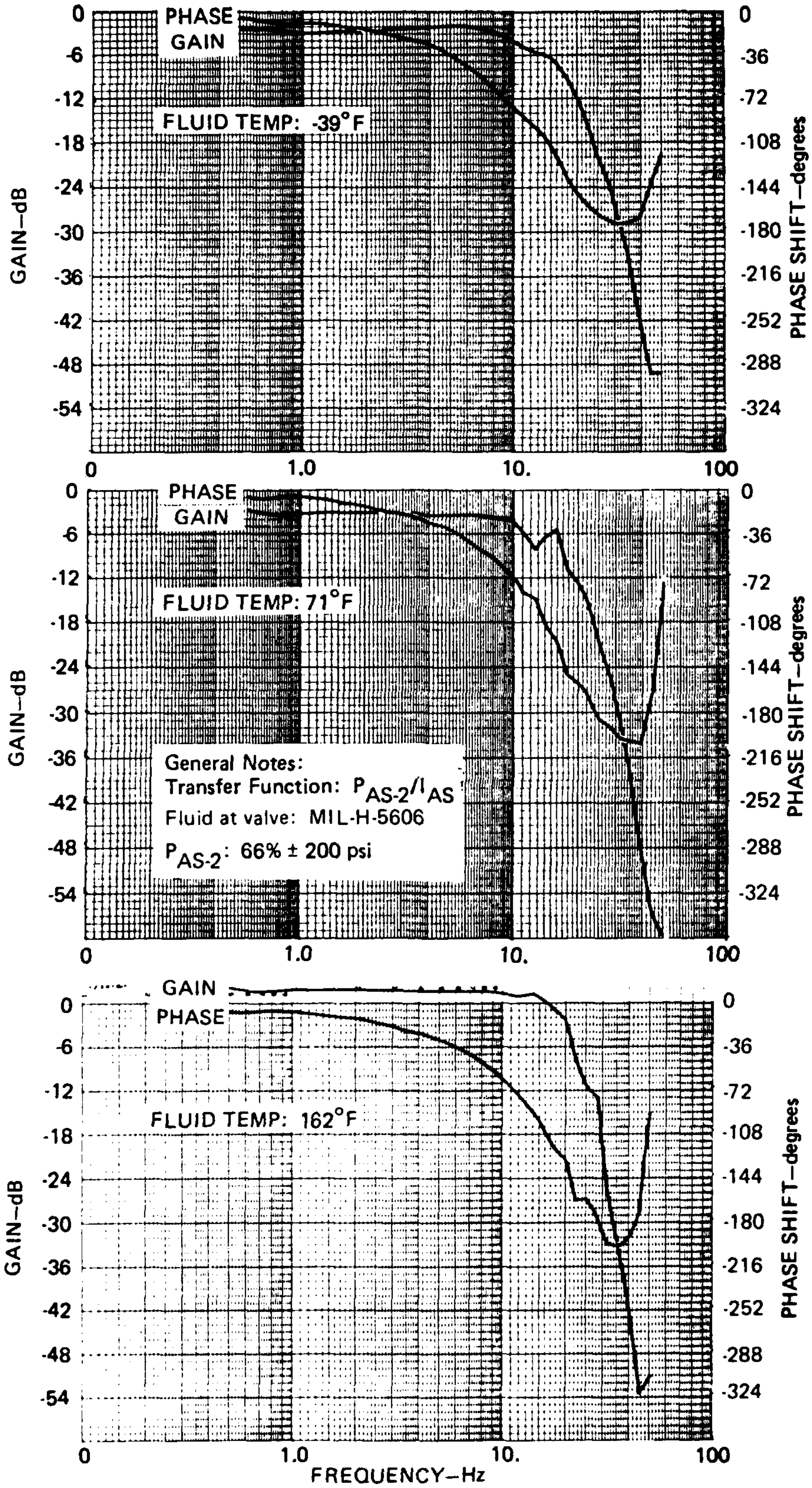


Figure D.80. Two-Fluid System Antiskid Valve Performance Variation with Temperature

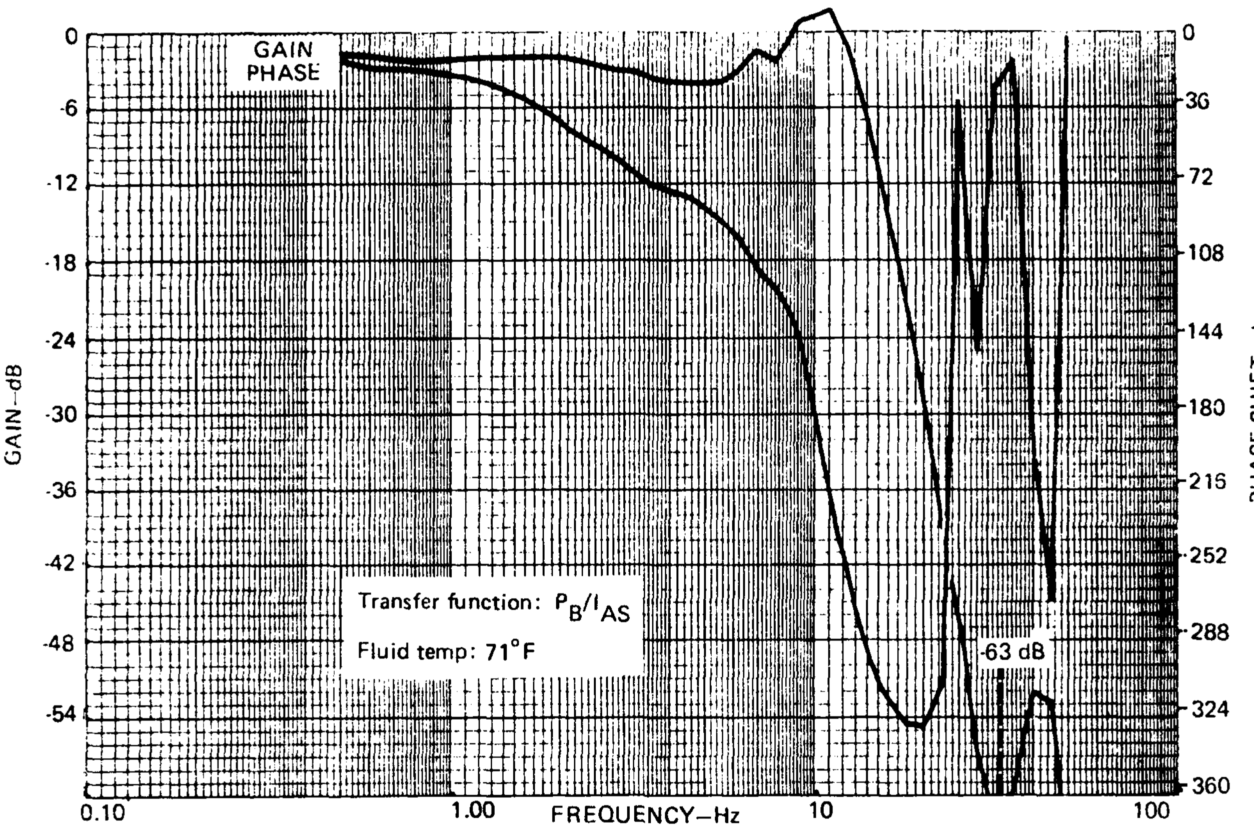


Figure D.81. Two-Fluid Brake System Frequency Response at Room Temperature, 33% ± 100 psi

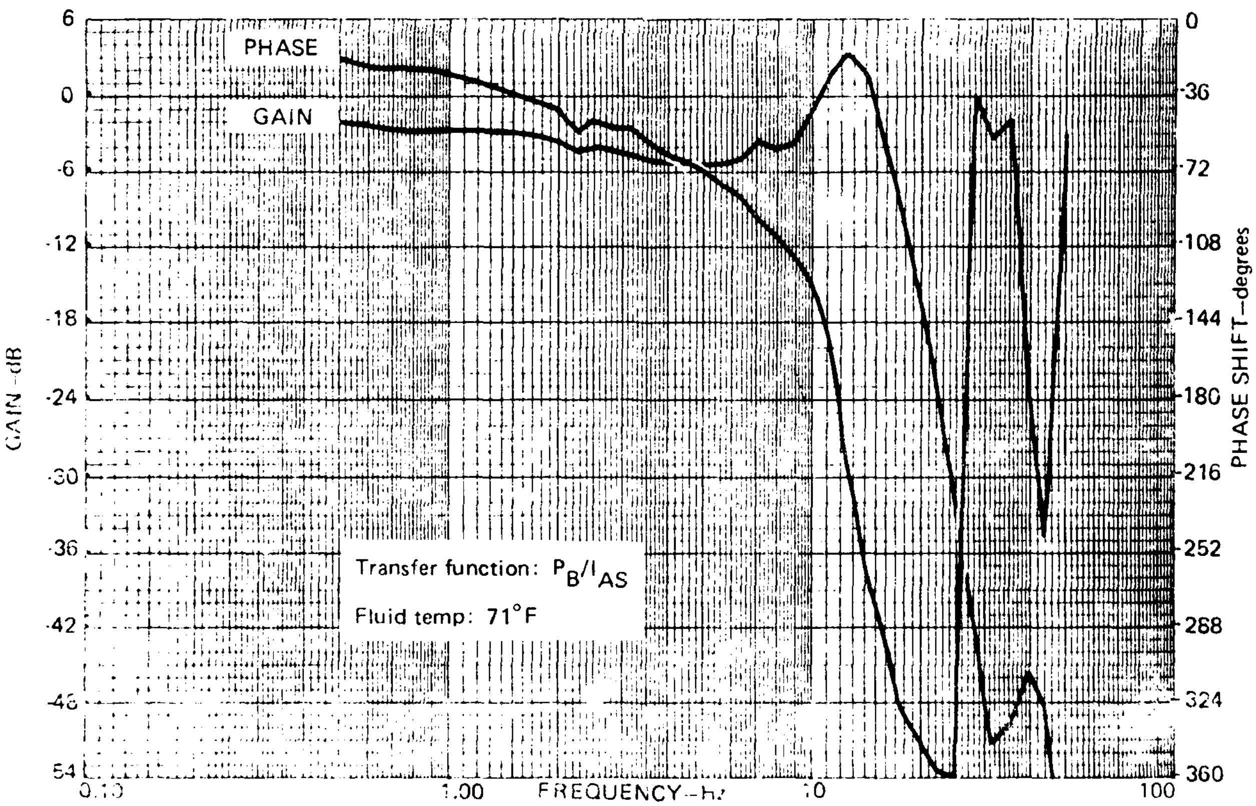


Figure D.82. Two-Fluid Brake System Frequency Response at Room Temperature, 66% ± 200 psi

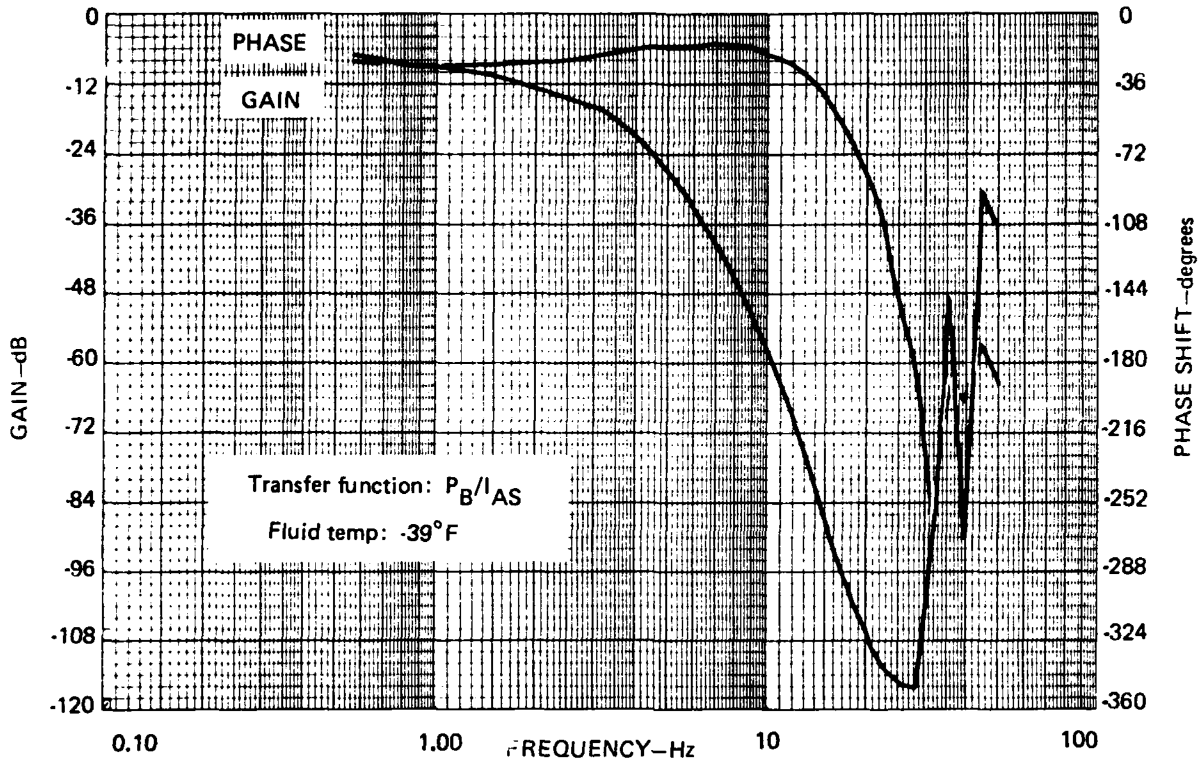


Figure D.83. Two-fluid Brake System Frequency Response at -40° F, 33% ± 100 psi

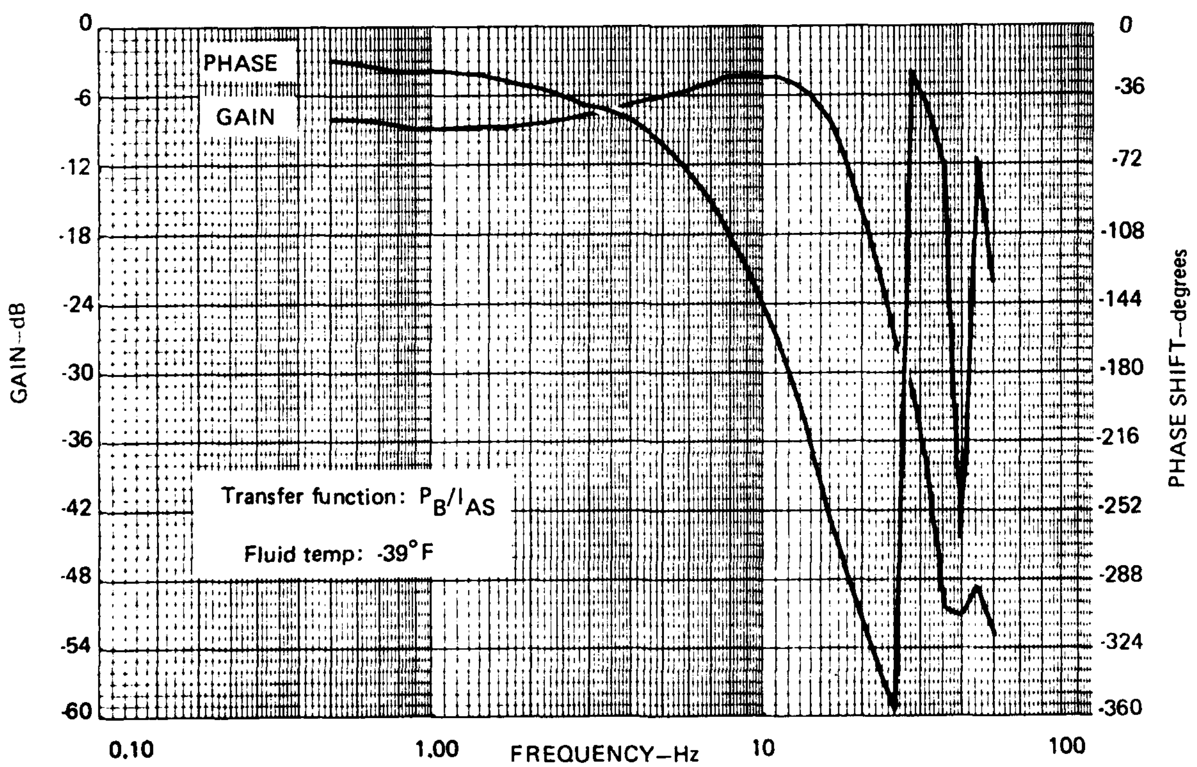


Figure D.84. Two-fluid Brake System Frequency Response at -40° F, 66% ± 200 psi

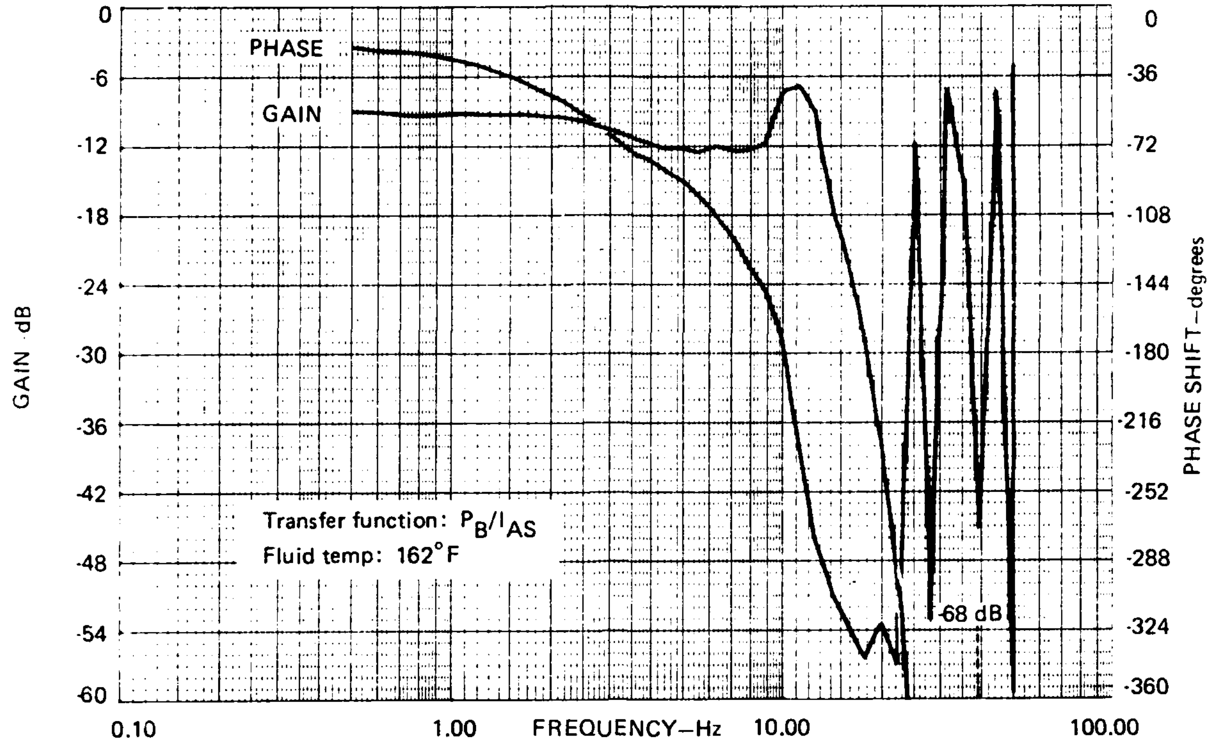


Figure D.85. Two-Fluid Brake System Frequency Response at 160°F, 33% ± 100 psi

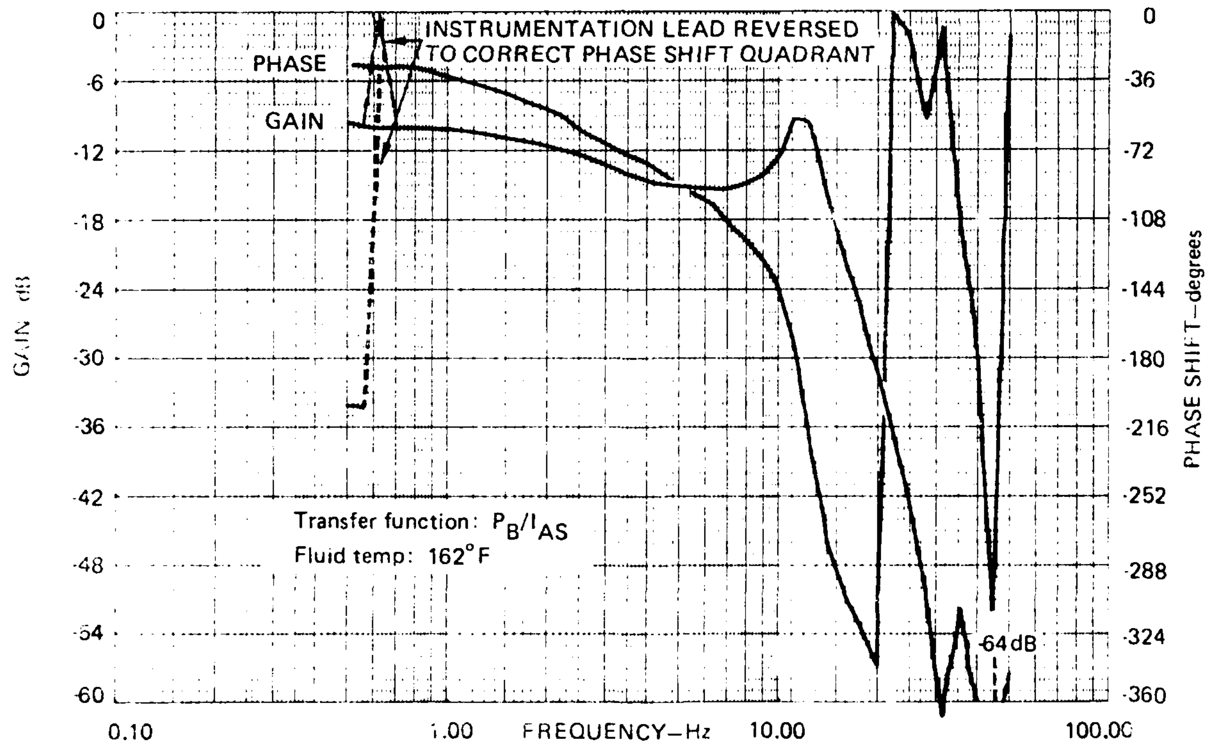


Figure D.86. Two-Fluid Brake System Frequency Response at 160°F, 66% ± 200 psi

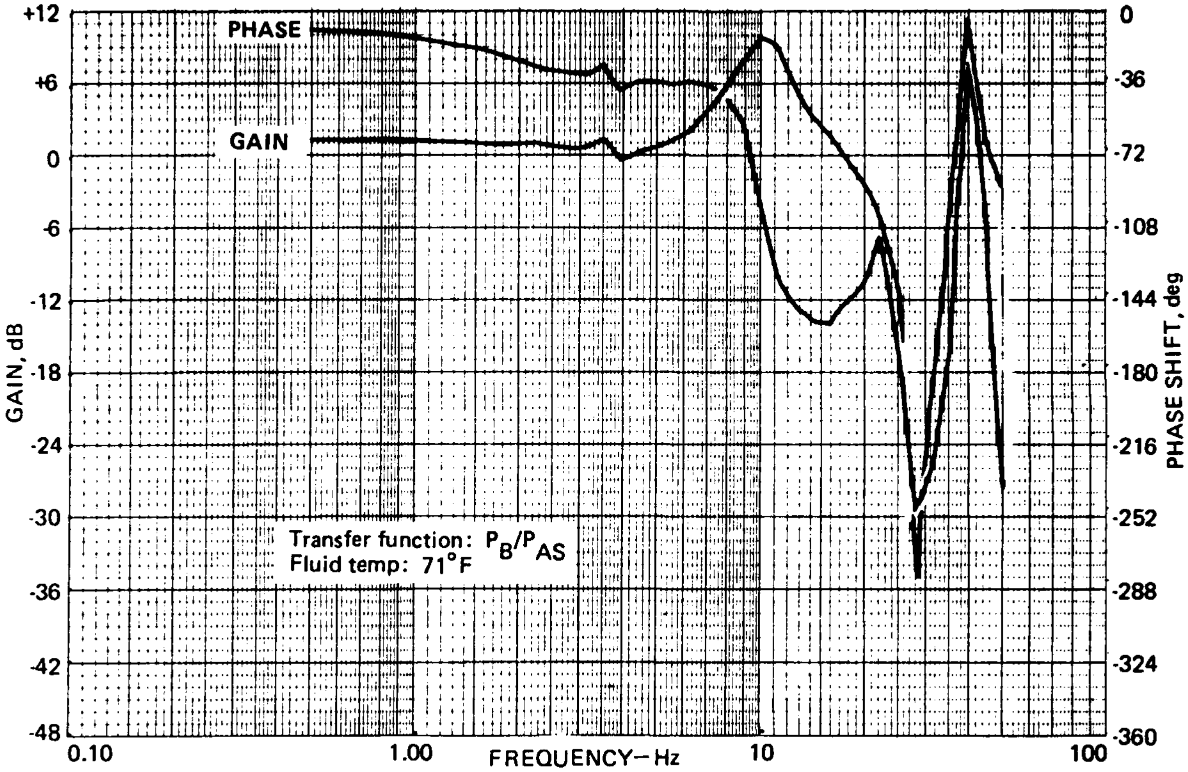


Figure D.87. Two-Fluid Brake Hydraulic System Frequency Response at Room Temperature, 33% ± 100 psi

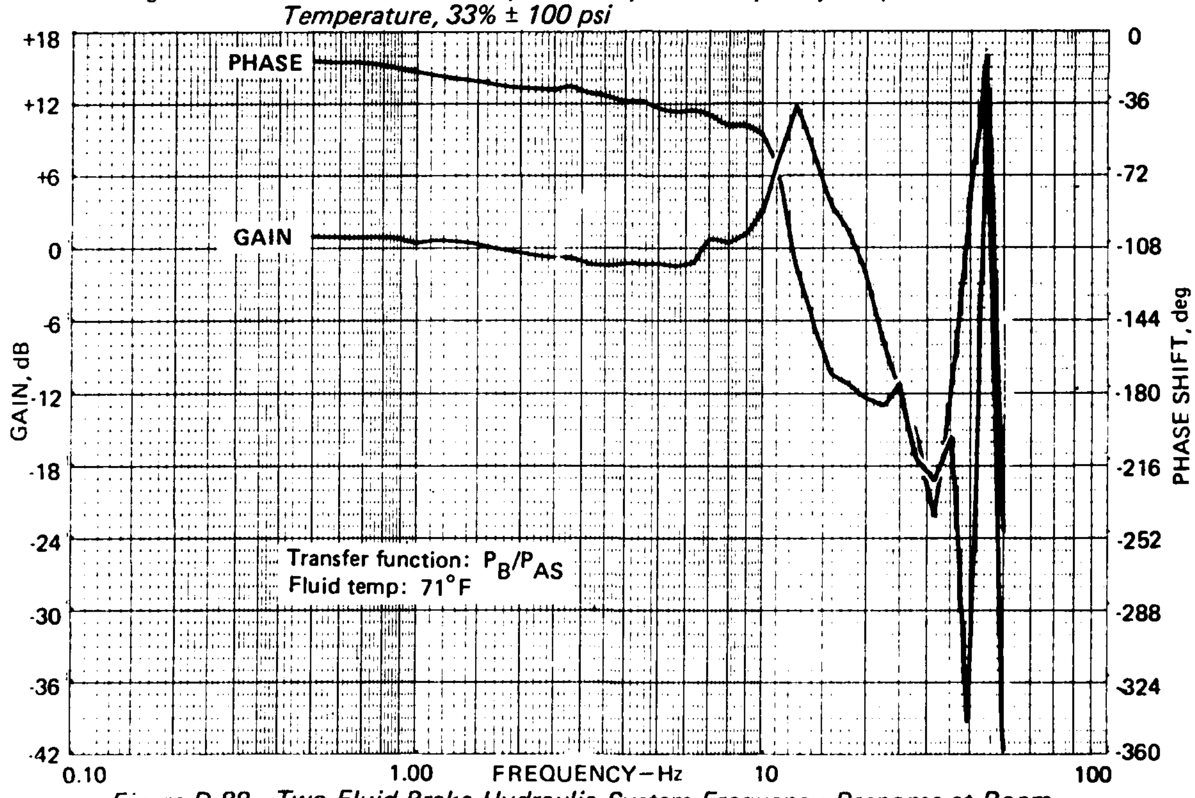


Figure D.88. Two-Fluid Brake Hydraulic System Frequency Response at Room Temperature, 66% ± 200 psi

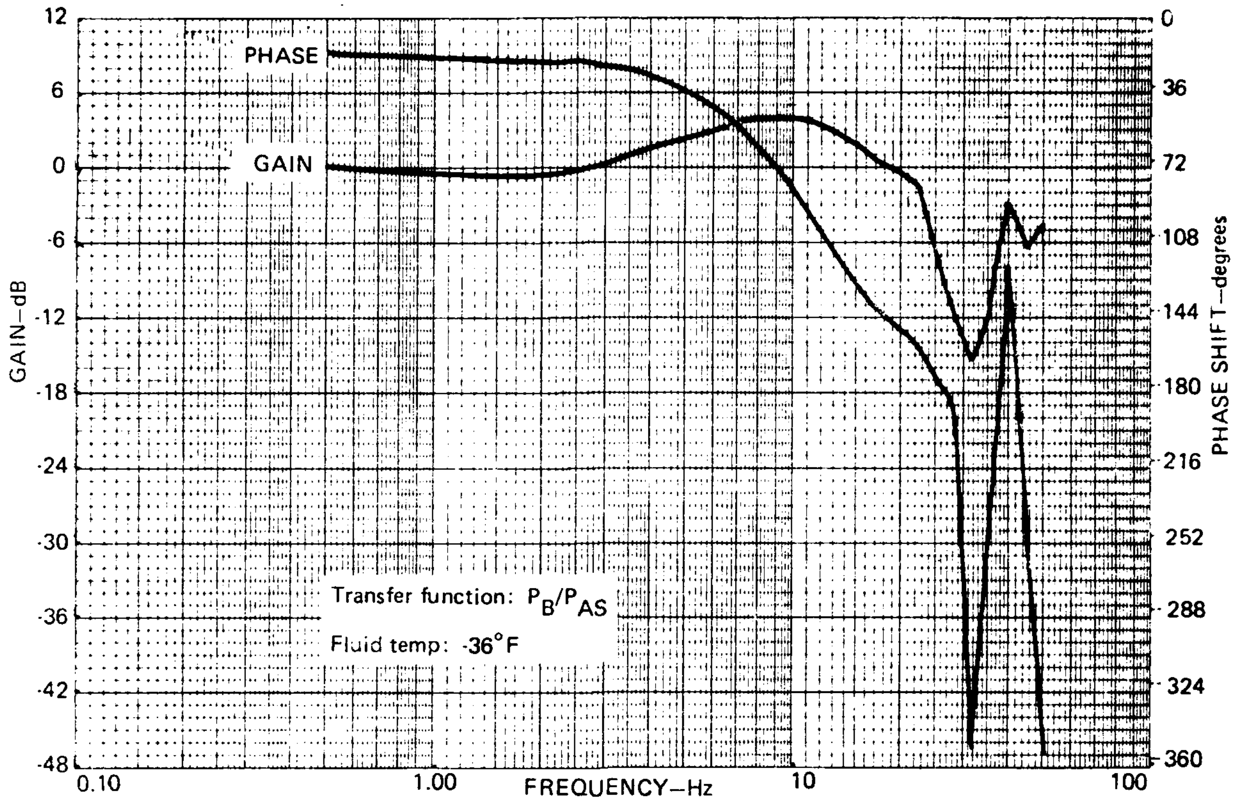


Figure D.89. Two-Fluid Brake Hydraulic System Frequency Response at -40° F, 33% ± 100 psi

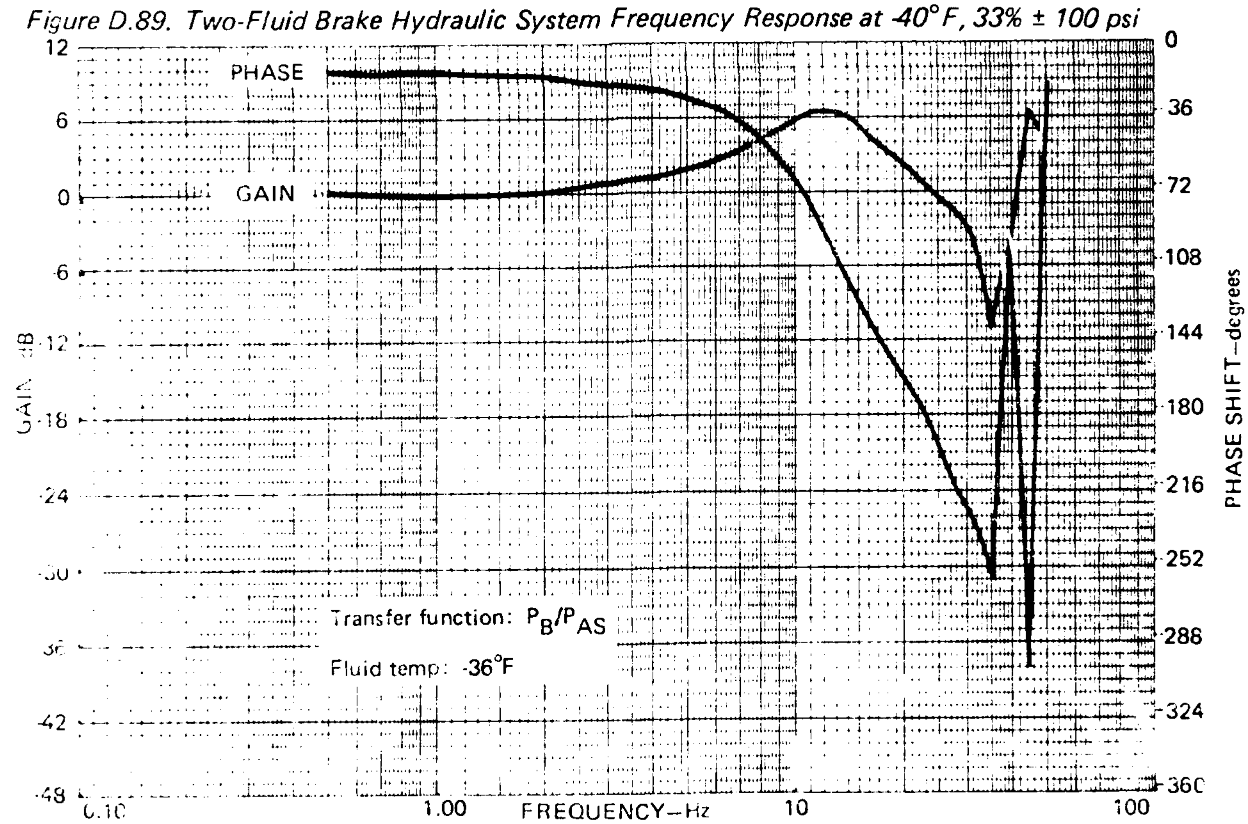


Figure D.90. Two-Fluid Brake Hydraulic System Frequency Response at -40° F, 66% ± 200 psi

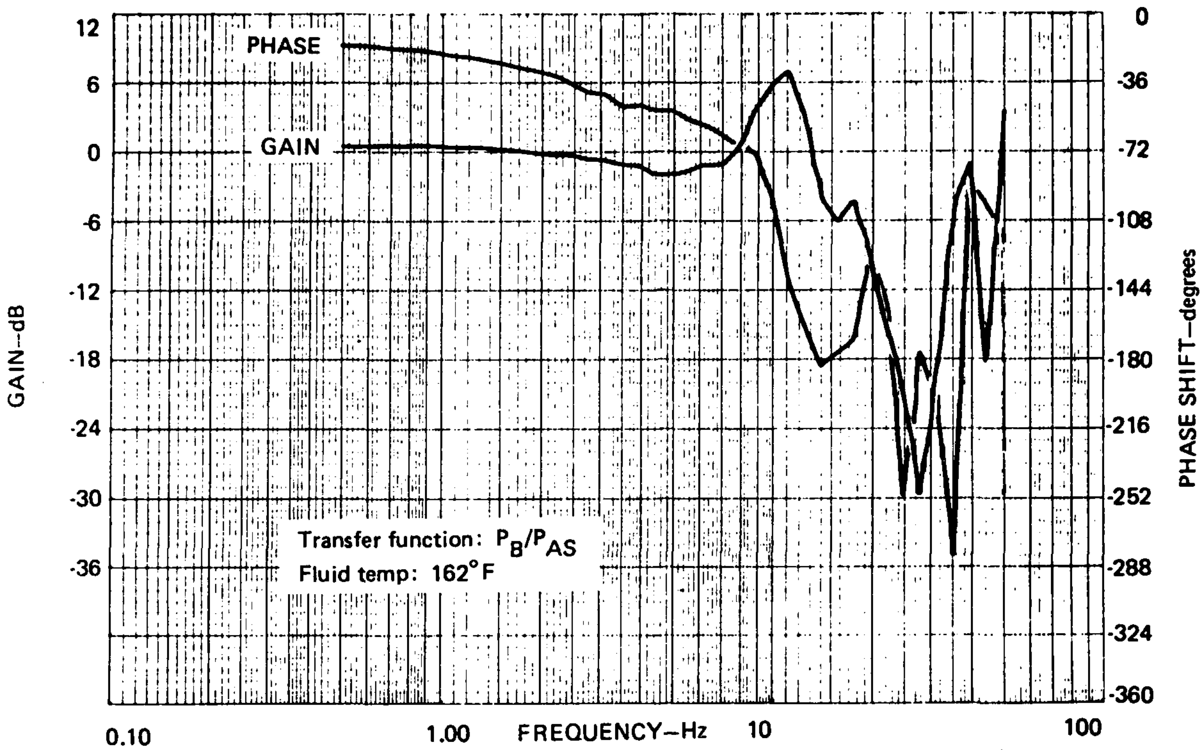


Figure D.91. Two-Fluid Brake Hydraulic System Frequency Response at 160° F, 33% ± 100 psi

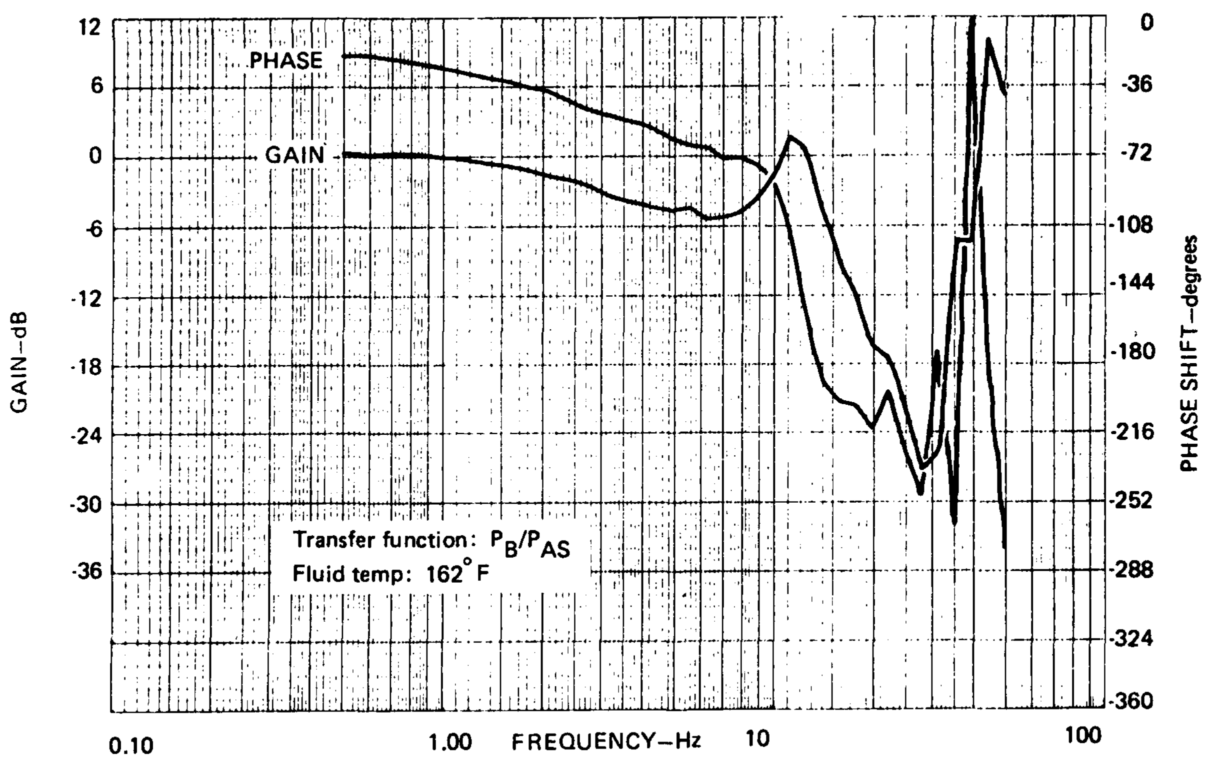


Figure D.92. Two-Fluid Brake Hydraulic System Frequency Response at 160° F, 66% ± 200 psi

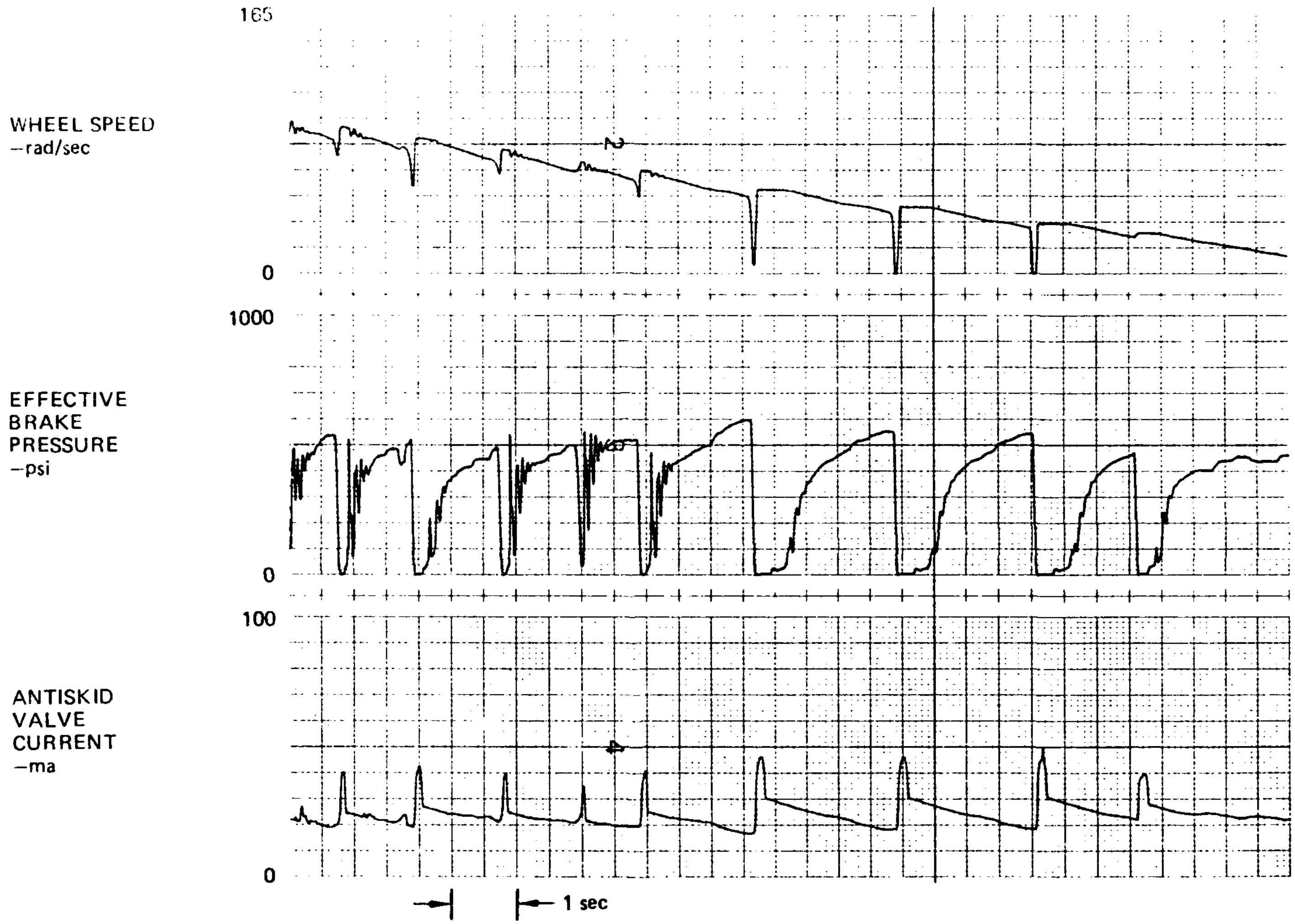


Figure D.93. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.6

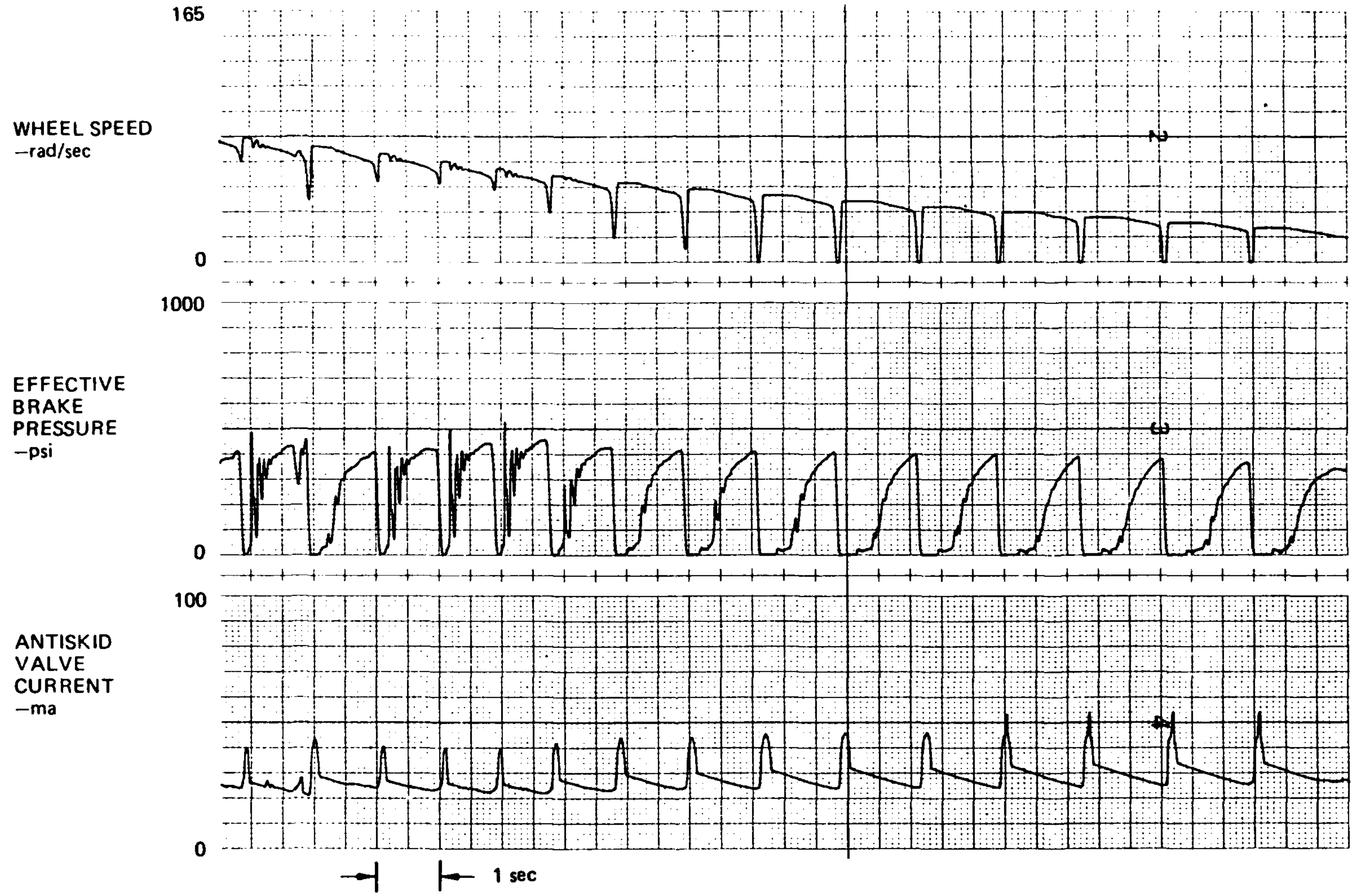


Figure D.94. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.5

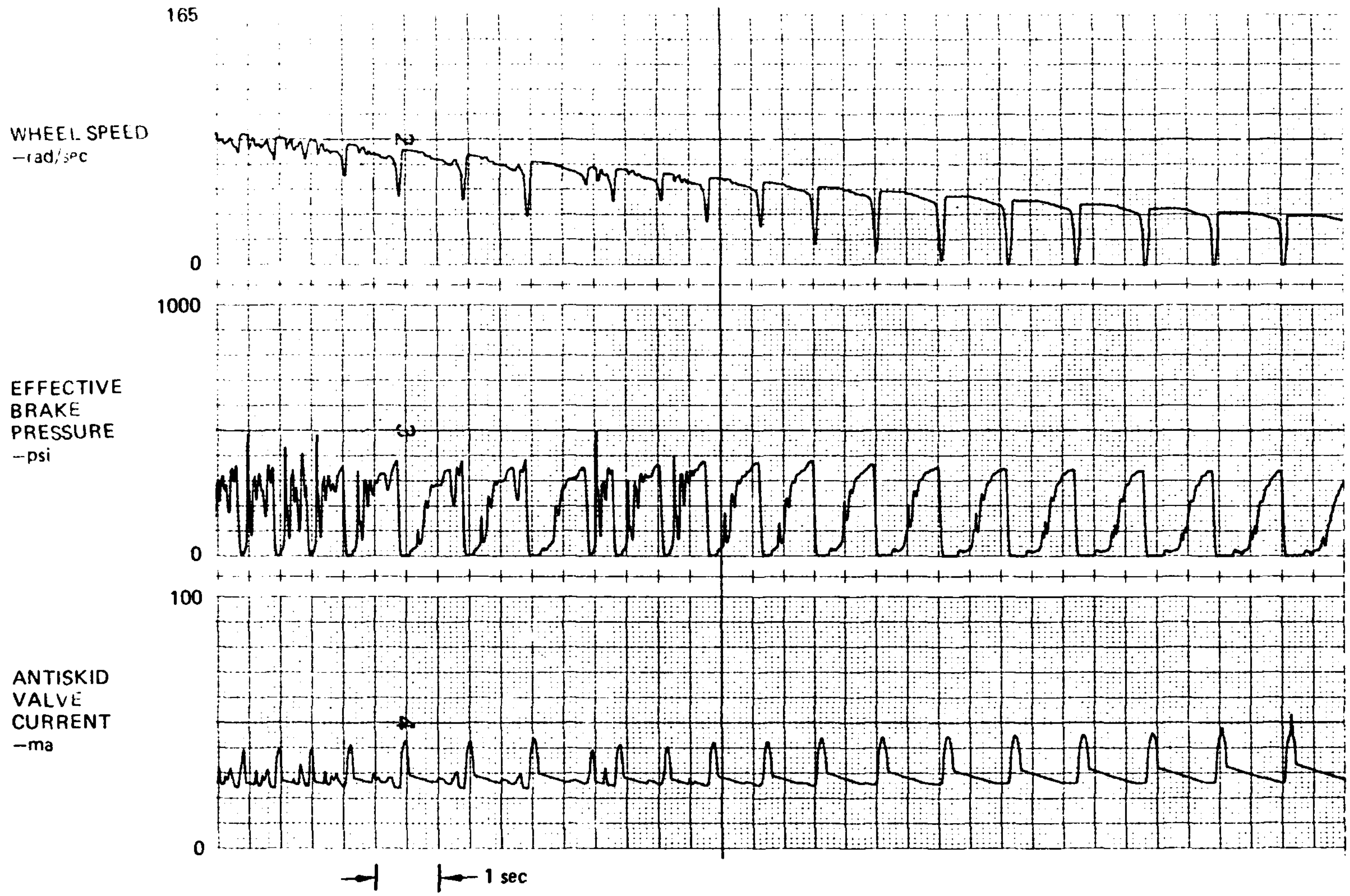


Figure D.95. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.4

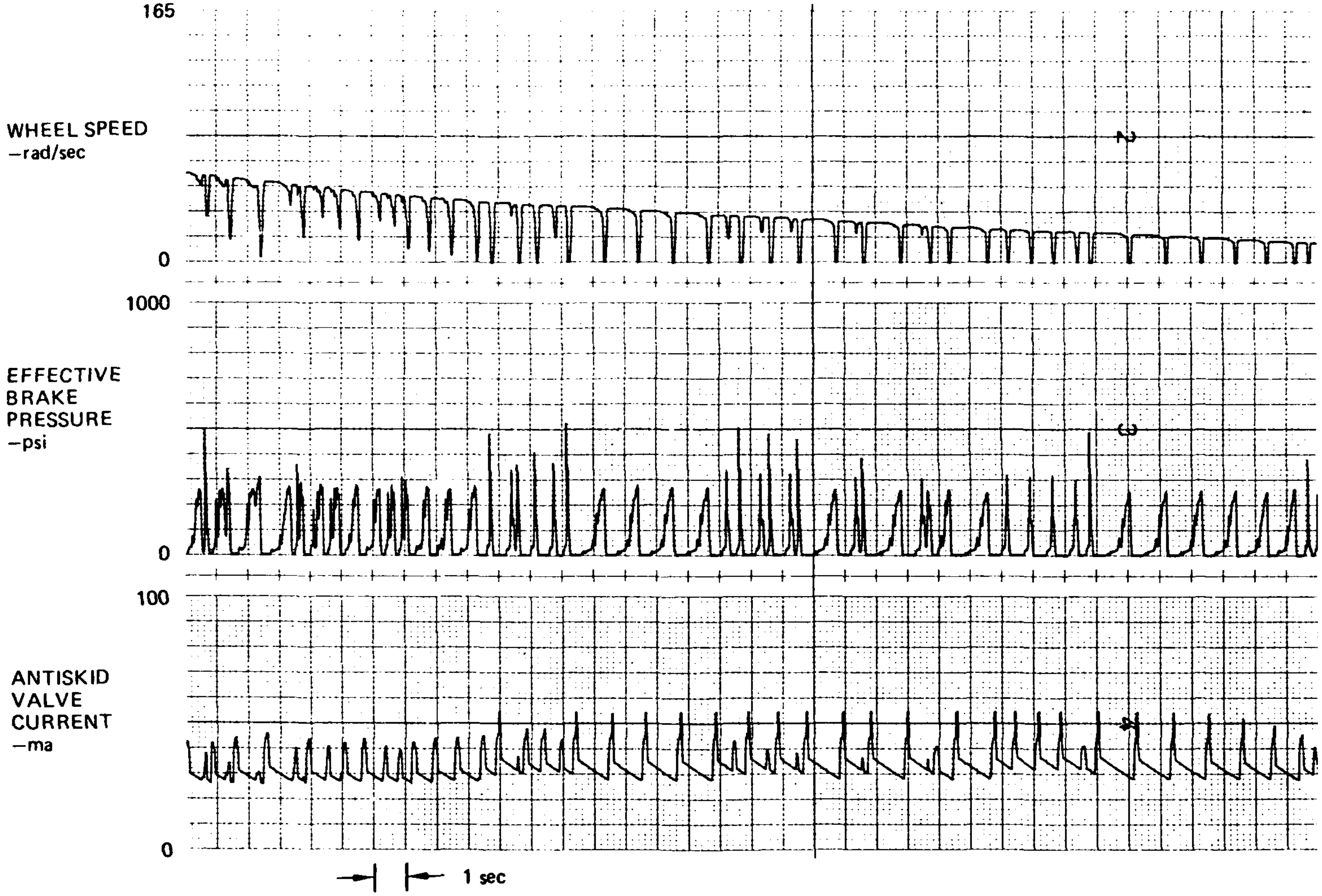


Figure D.96. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.3

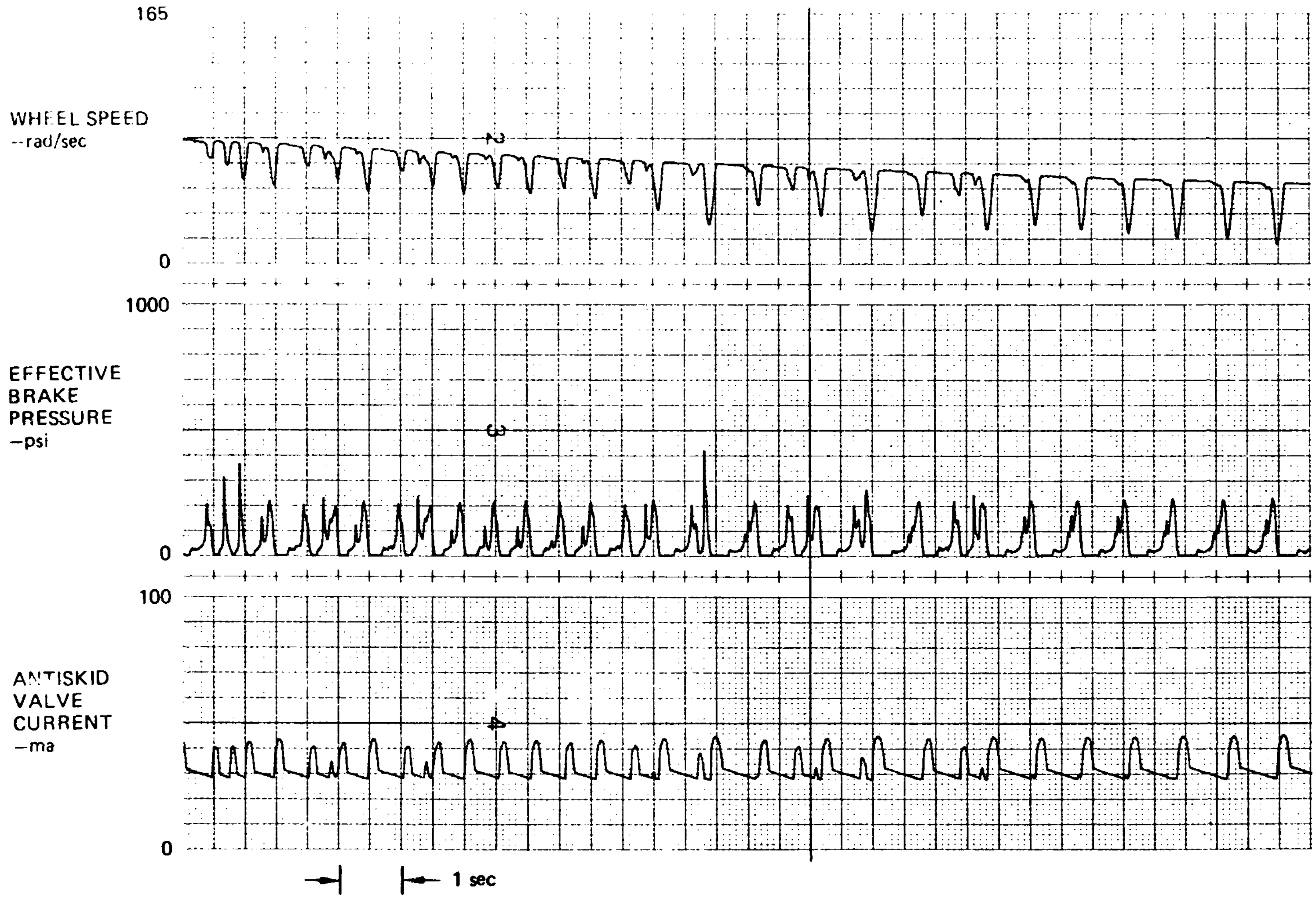


Figure D.97. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.2

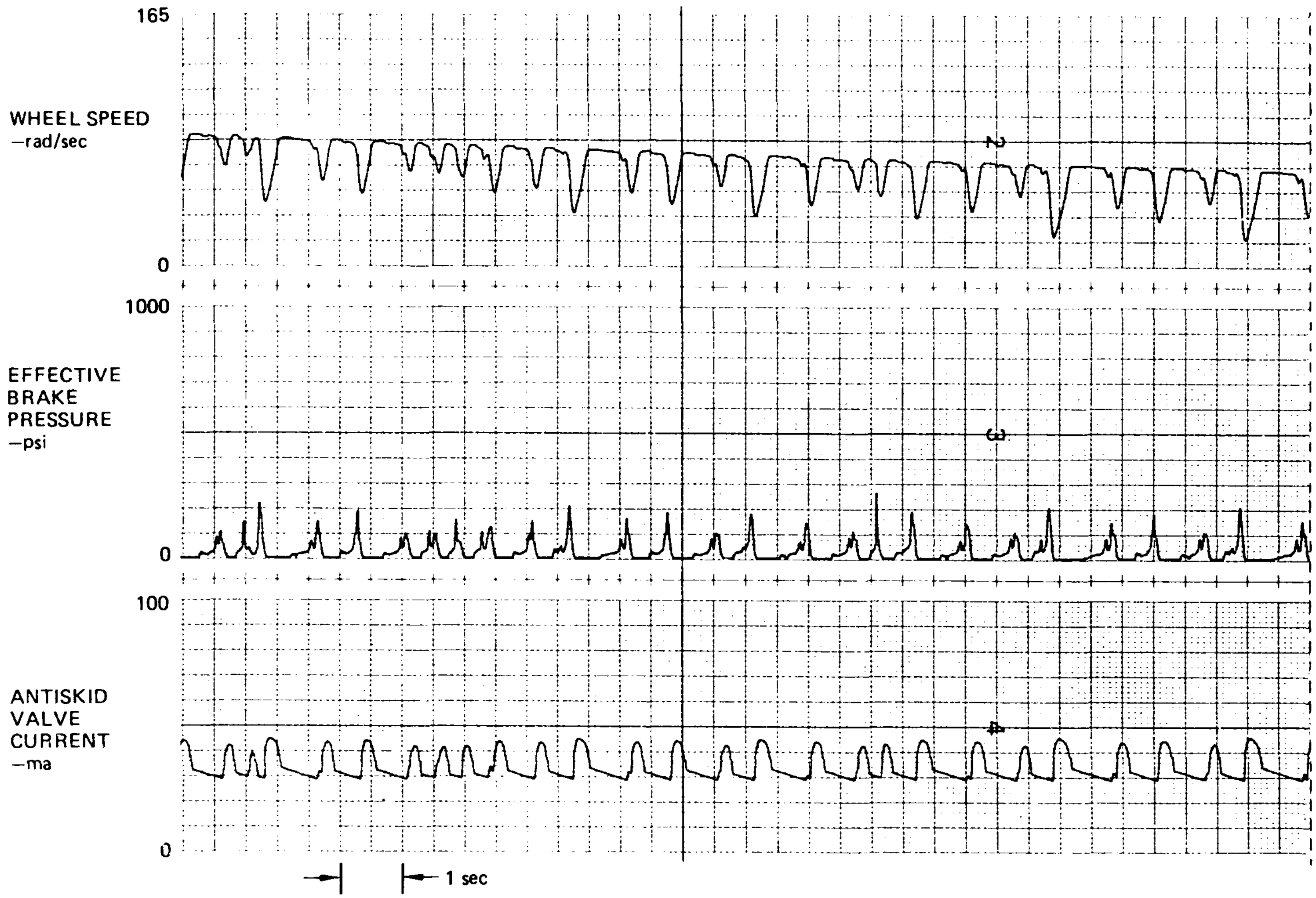


Figure D.98. Two-Fluid Brake System Performance at Room Temperature, Mu = 0.1

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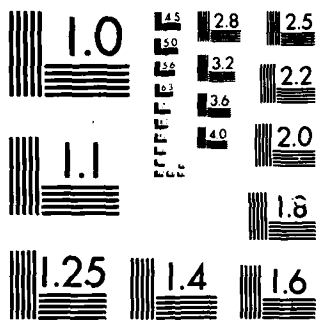

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Figure D.99. Two-Fluid Brake System Performance at -40°F, Mu = 0.6

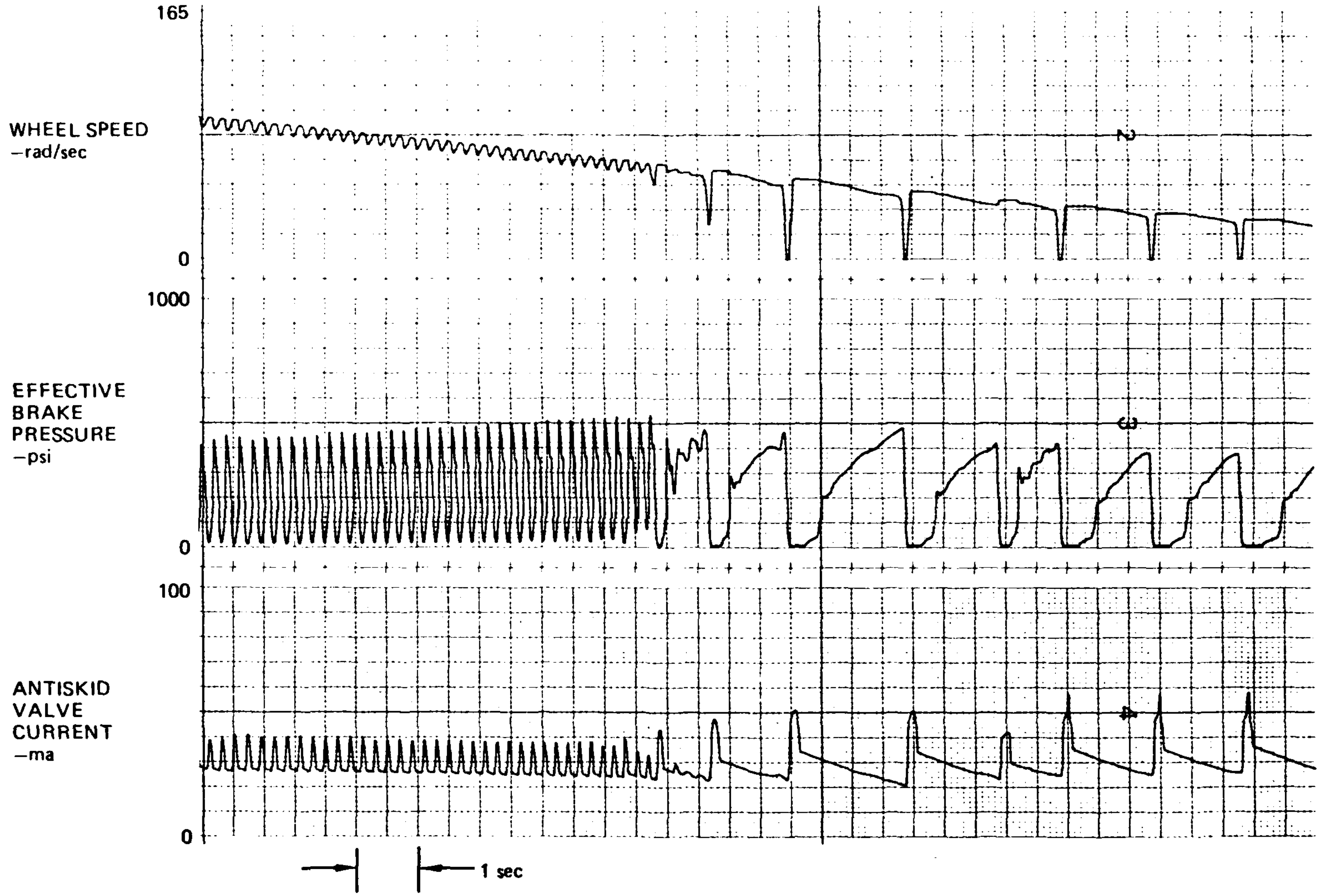

Figure D.100. Two-Fluid Brake System Performance at -40°F, Mu = 0.5

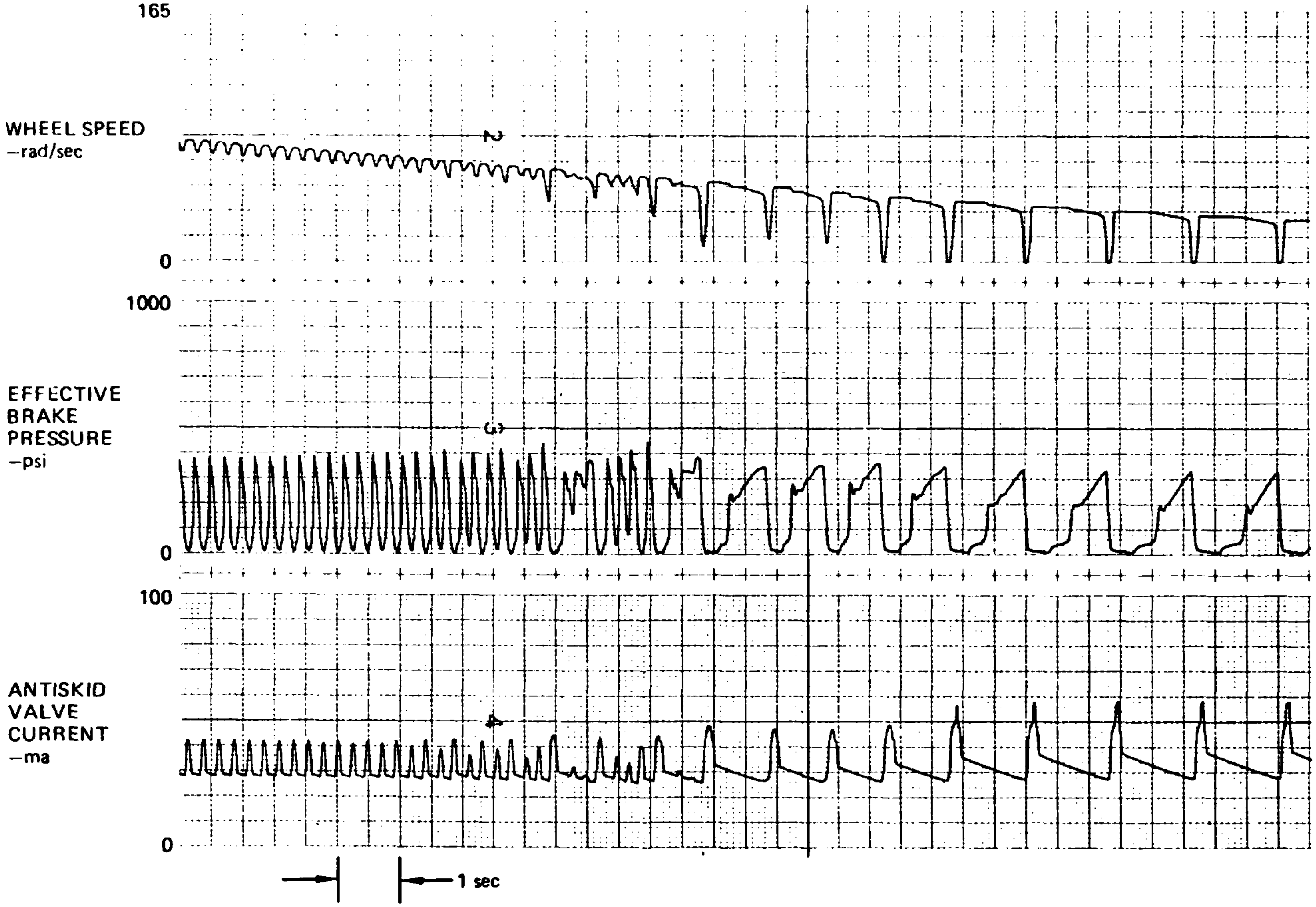

Figure D.101. Two-Fluid Brake System Performance at -40°F, Mu = 0.4

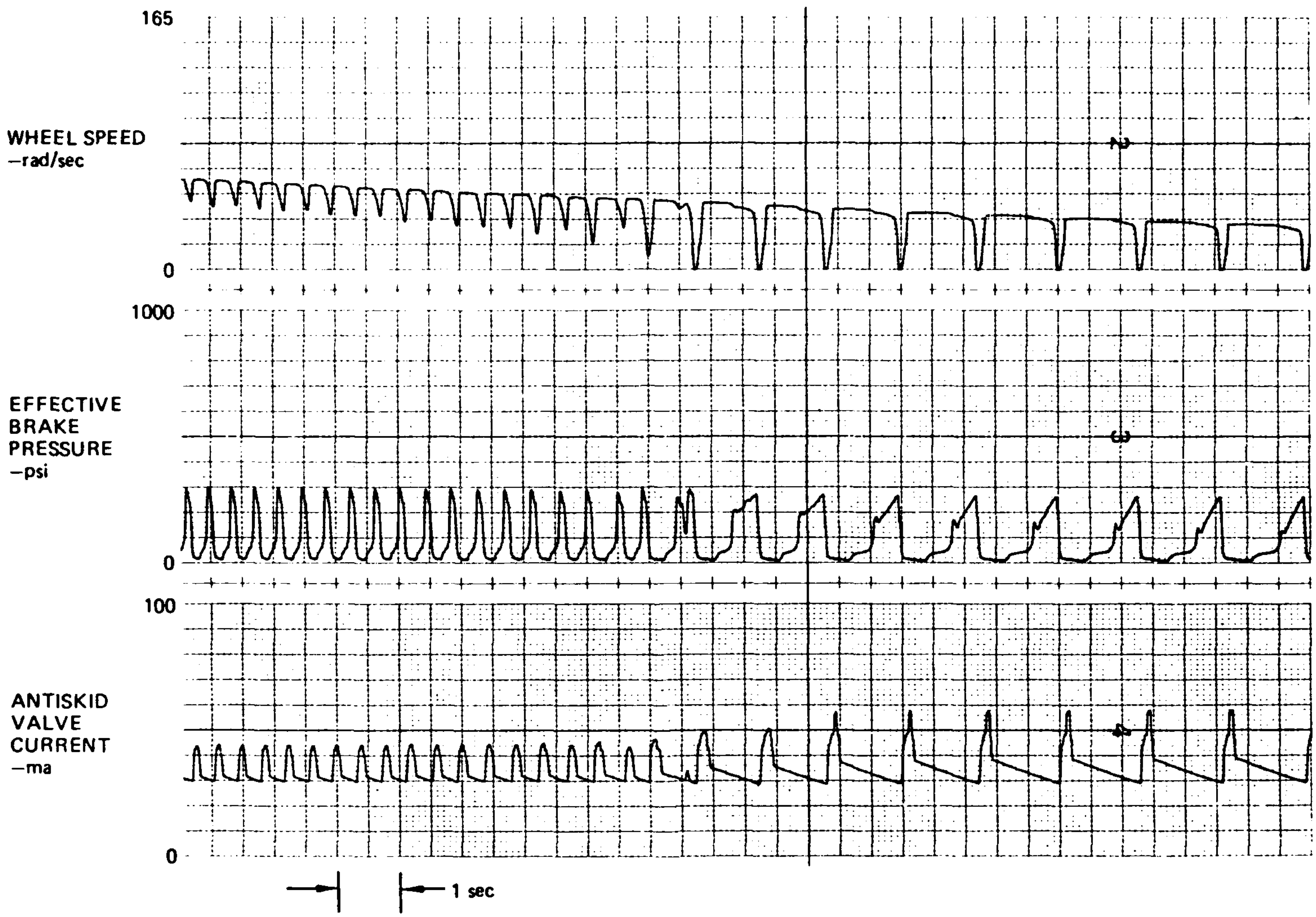

Figure D.102. Two-Fluid Brake System Performance at -40^{o}F, Mu = 0.3

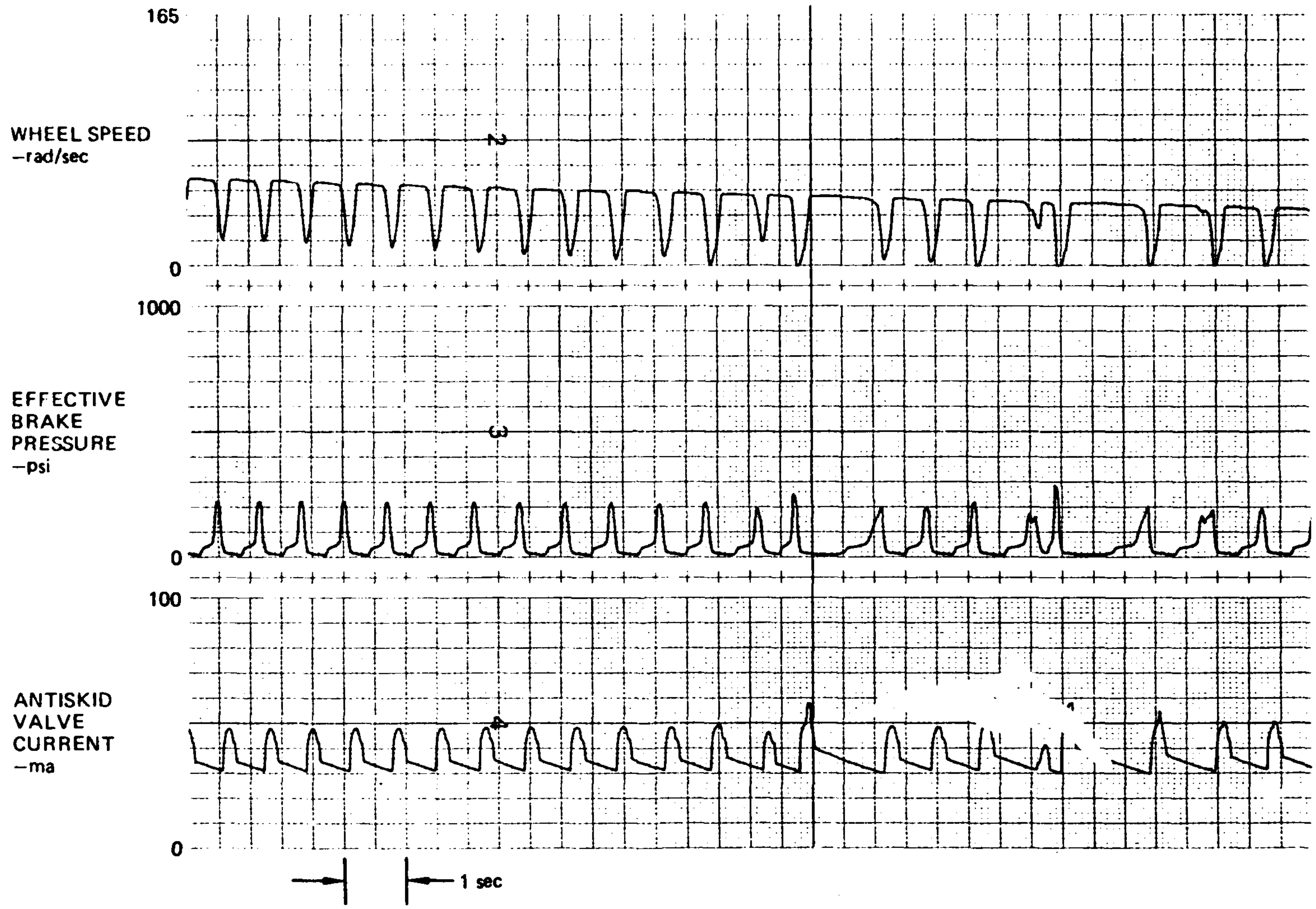

Figure D.103. Two-Fluid Brake System Performance at -40 °F, Mu = 0.2

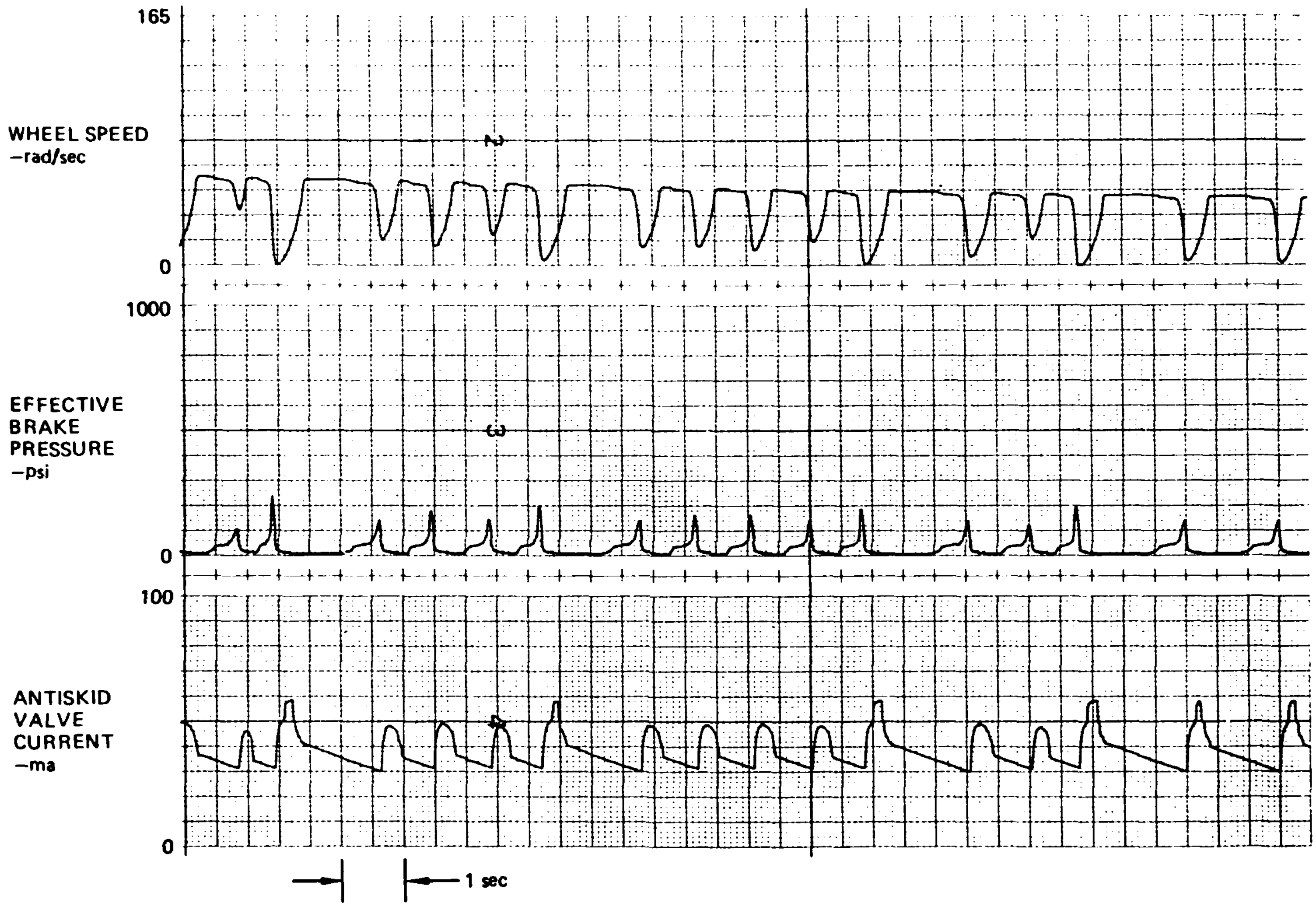

Figure D.104. Two-Fluid Brake System Performance at -40°F, Mu = 0.1

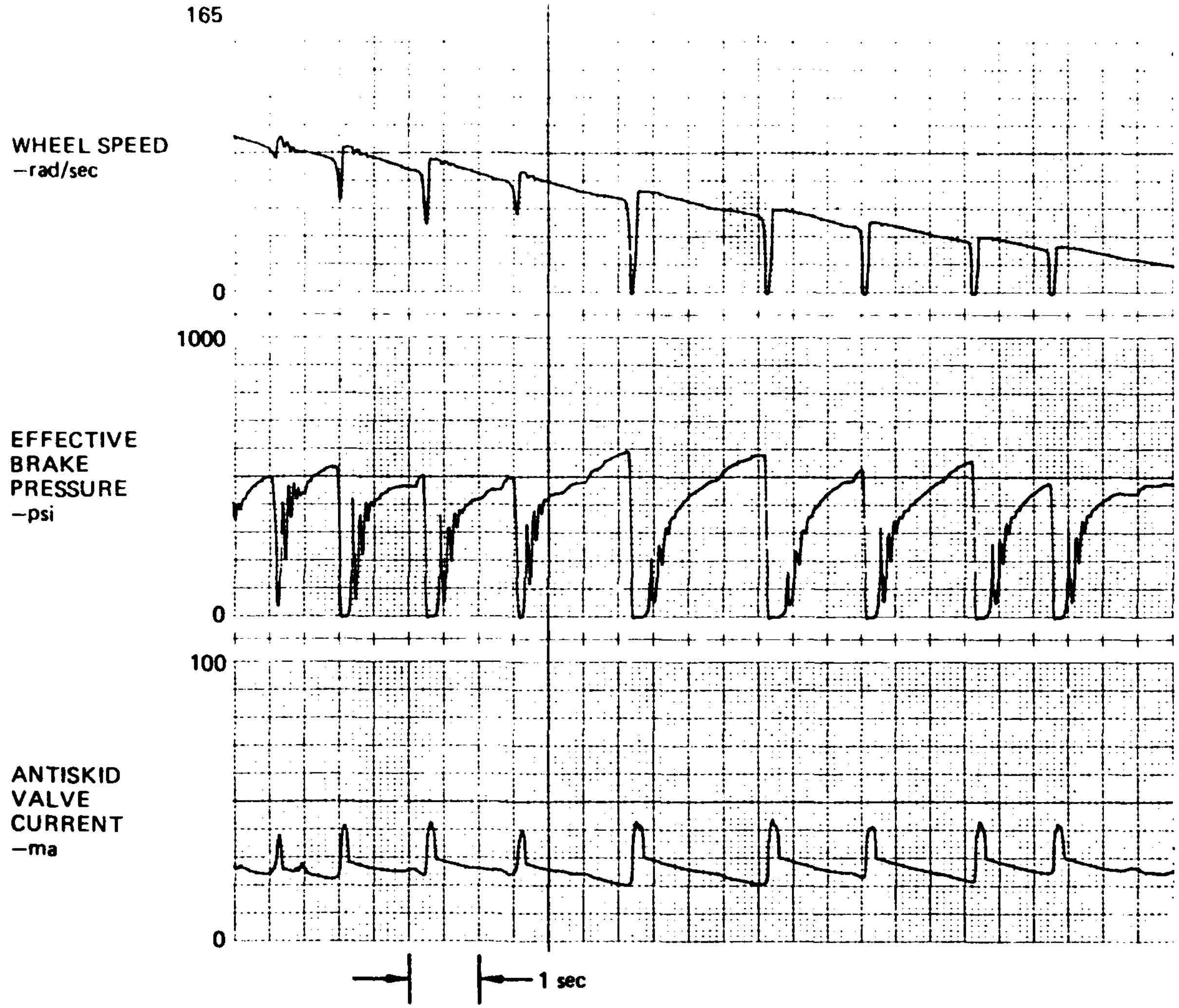

Figure D.105. Two-Fluid Brake System Performance at 160°F, Mu = 0.6

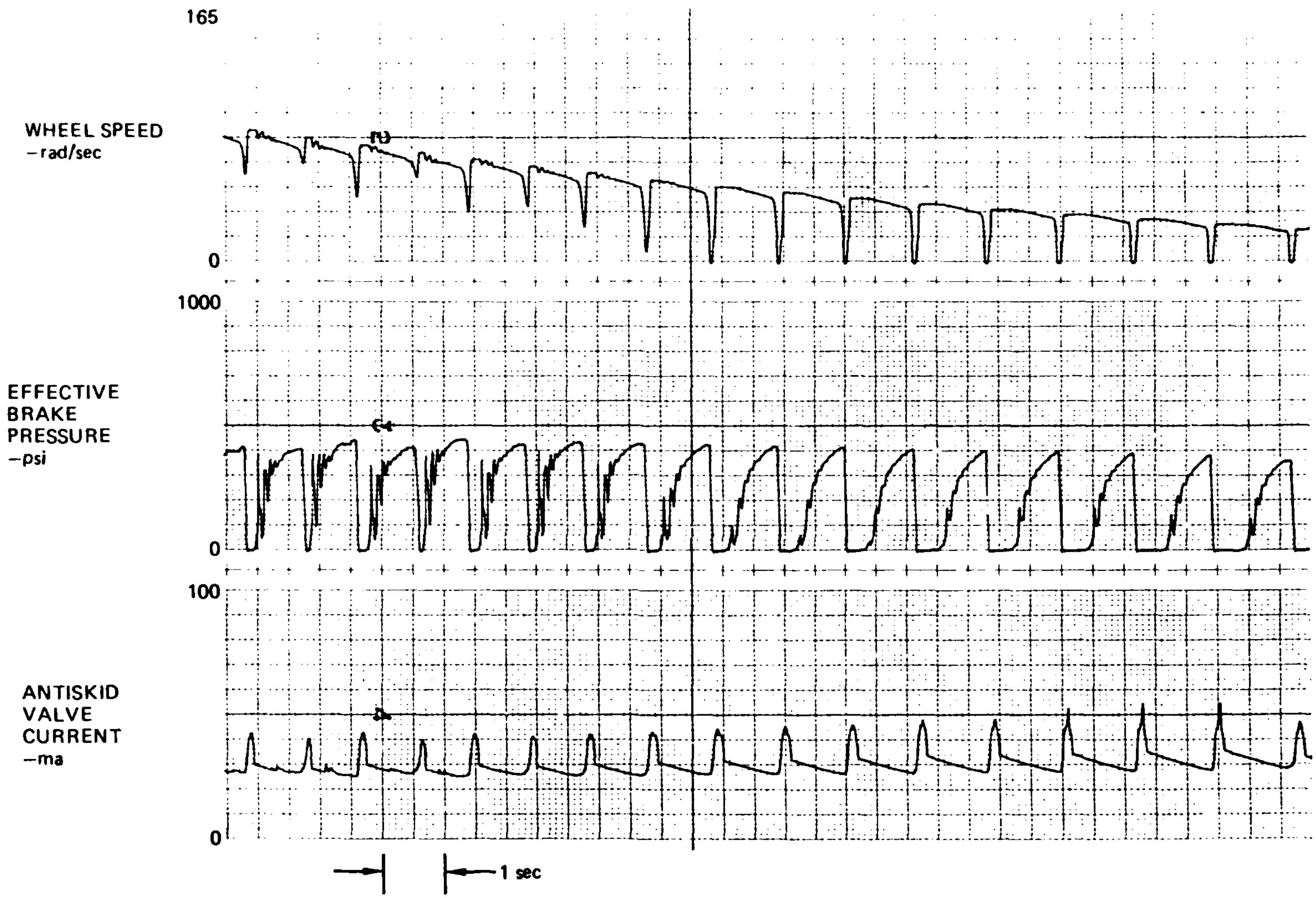

Figure D.106. Two-Fluid Brake System Performance at 160^{o}F, Mu = 0.5

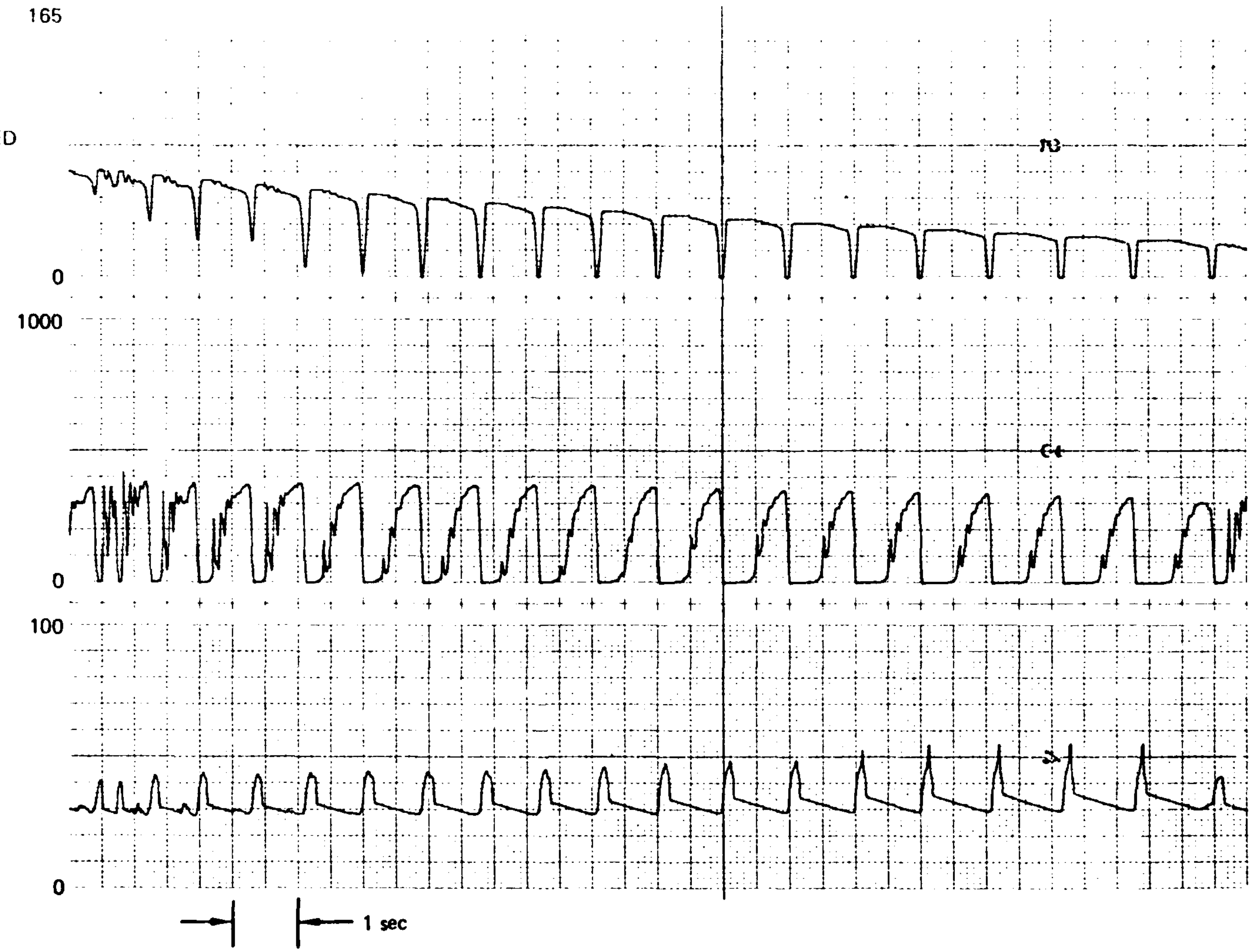

Figure D.107. Two-Fluid Brake System Performance at 160^{o}F, Mu = 0.4

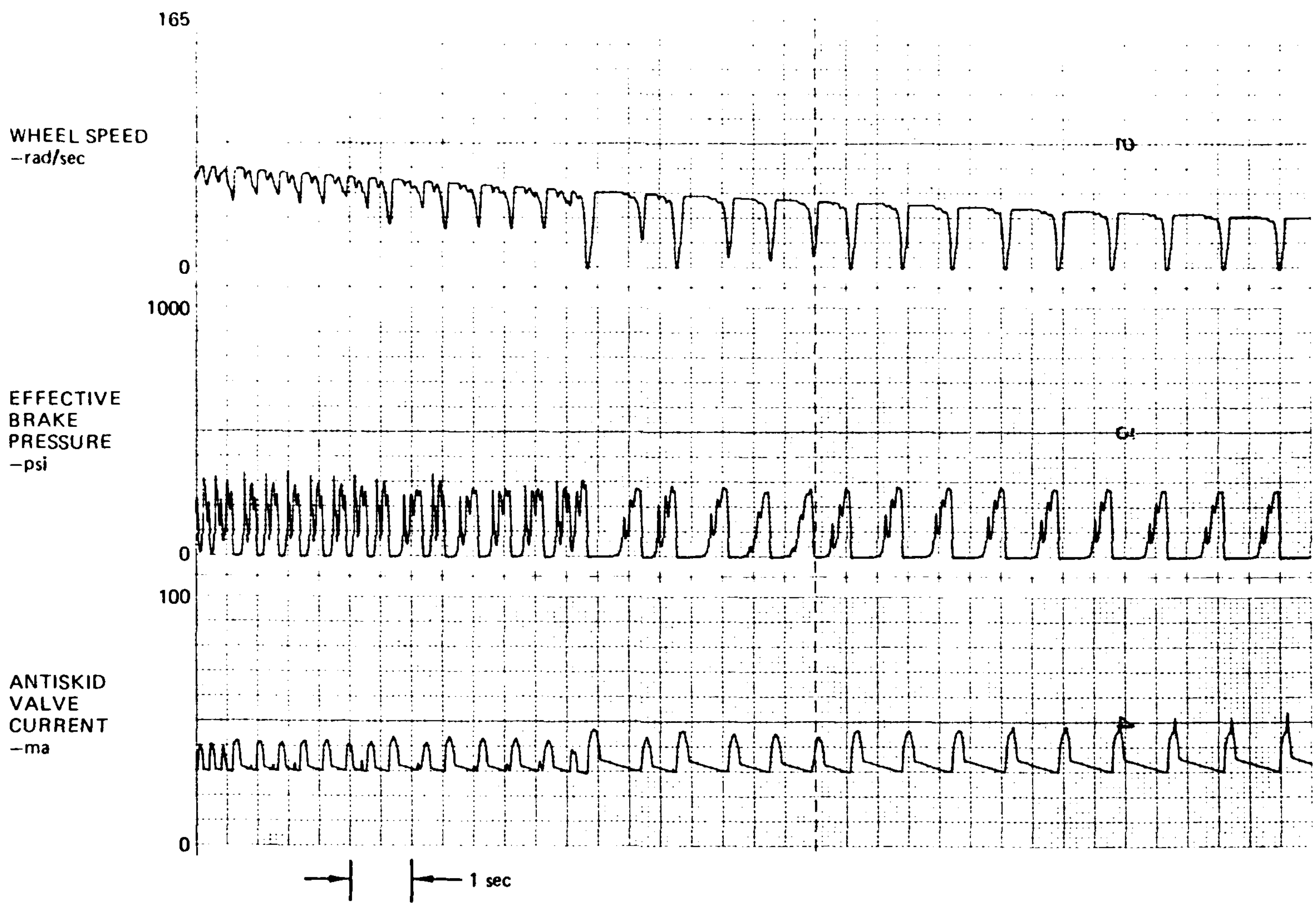

Figure D.108. Two-Fluid Brake System Performance at 160^{o}F, Mu = 0.3

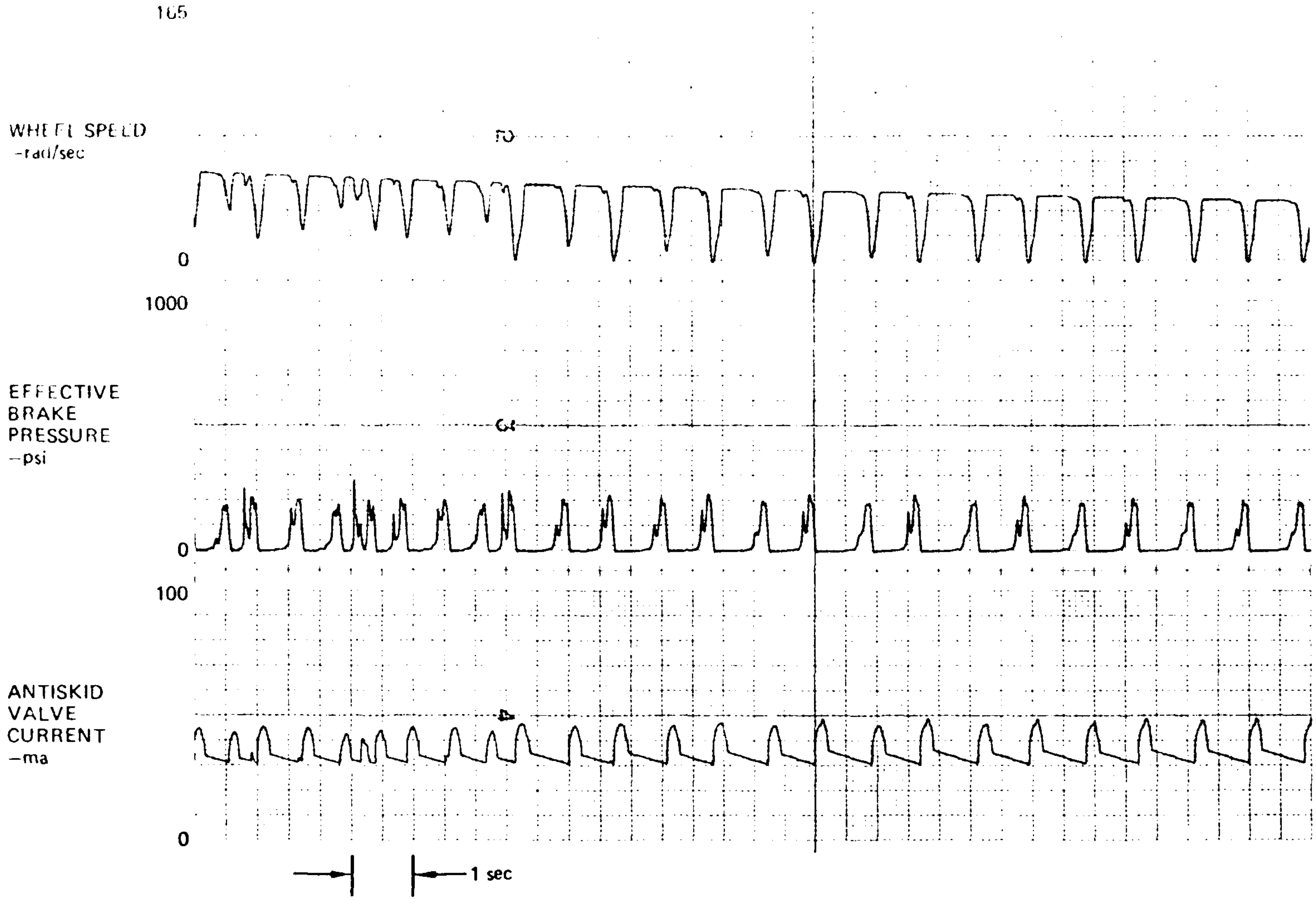

Figure D.109. Two-Fluid Brake System Performance at 160°F, Mu = 0.2

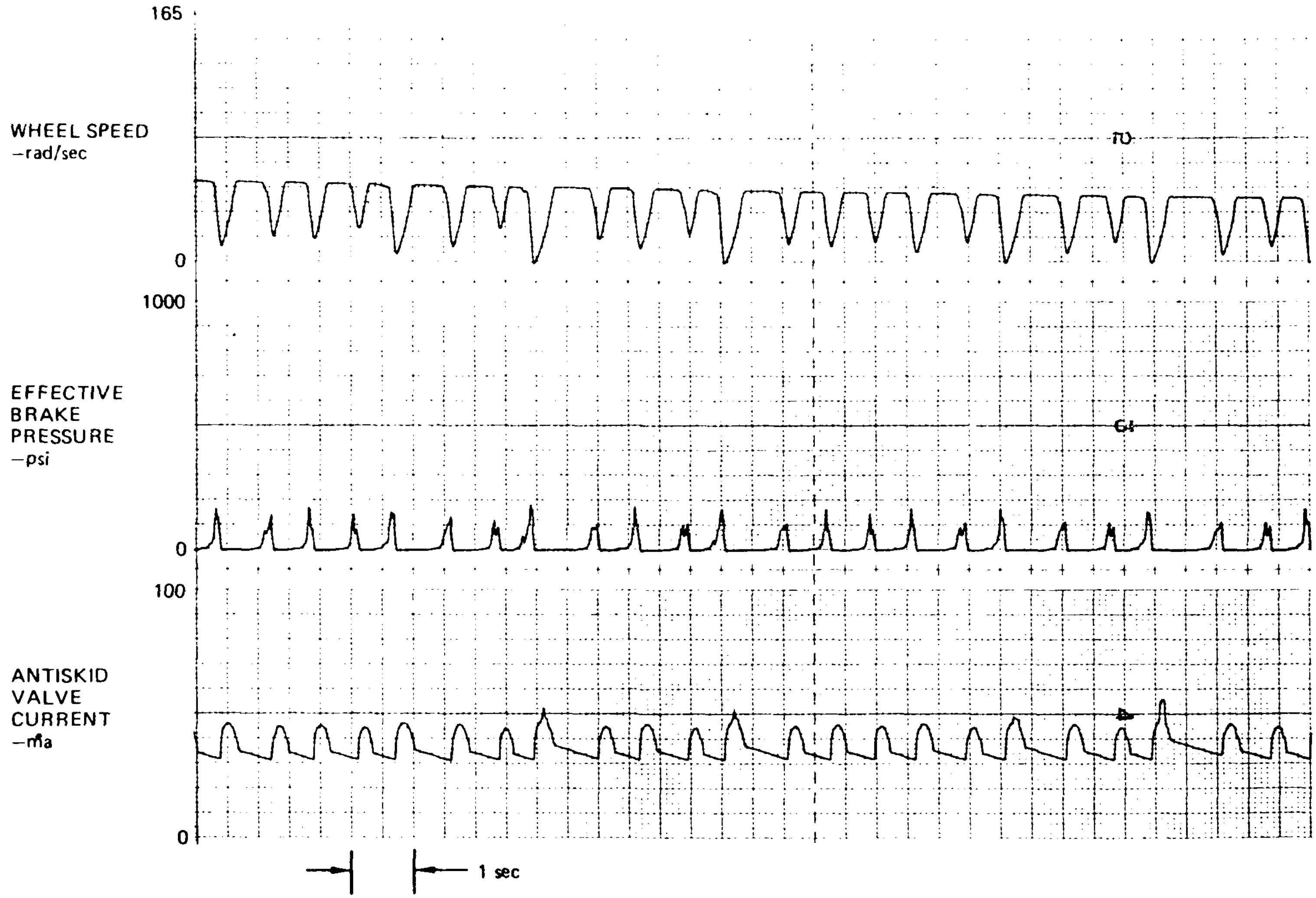

Figure D.110. Two-Fluid Brake System Performance at 160°F, Mu = 0.1

APPENDIX E

FLIGHT TEST DEMONSTRATION PROCEDURE

This appendix contains in total the document, Revision B, dated April 1, 1985, that provided the recommended procedures for the flight test demonstration of the FHBS.

The page and figure numbers have been changed from those in the document previously delivered to the USAF to be compatible with the format of this report.

FIREPROOF HYDRAULIC BRAKE SYSTEM

Contract F33615-83-C-2322

CDRL 12

Flight Test Demonstration Procedure

Released - October 2, 1984

Revision A - February 13, 1985

Revision B - April 1, 1985

Prepared for:
Air Force Wright Aeronautical Laboratories
Aero Propulsion Laboratory
Attention: Mr. W. B. Campbell, AFWAL/POOS

Prepared by: D. W. Huling
D. W. Huling

Approved by:
M. L. Holmdahl
Program Manager

Fireproof Hydraulic Brake System
Flight Test Demonstration Procedure

I. Introduction

The Boeing Military Airplane Company proposes this Flight Test Demonstration Procedure, which will provide that data required to meet the objectives of demonstrating the Fireproof Hydraulic Brake System (FHBS) concept and verify equivalent stopping performance compared to the existing MIL-H-5606 fluid brake system. The procedure includes a detail flight test plan, recommended instrumentation/recordings, data reduction description, test article description, FHBS installation and maintenance instructions.

The dual fluid, FHBS provides a minimal modification to an existing hydraulic brake system that would greatly reduce the incidence/probability of hydraulic fires on Air Force aircraft. The FHBS kit equipment provided by Boeing for this demonstration flight test, will convert one of the four main gear wheel pairs such that a direct comparison of braking/stopping performance can be made.

The FHBS kit provided by Boeing contains all the components and parts required to accomplish the FHBS modification. The tubing provided is in straight lengths since the tube assemblies with bends must be tailored to the aircraft. The kit also includes a CTFE fluid servicing cart as Ground Service Equipment for filling and bleeding the CTFE fluid system.

The flight testing will required two phases of testing: Phase I - establish the existing "as is" C-135 brake performance, and Phase II - measure the FHBS brake performance. Each phase shall follow the test conditions described in Section IV.

II. Test Article Description

The Phase I of braking performance tests shall be conducted on the "as is" C-135E (S/N 60-0375). The aircraft shall be instrumented to provide the same data requirements as to be utilized for the FHBS (Phase II) tests as described below.

For Phase II, the FHBS is to be installed on C-135E, serial number 60-0375 which is equipped with a Mark II anti-skid system and five rotor brakes. The left, outboard maingear wheel pair was selected as the location for the FHBS demonstrator.

The FHBS modification results in the removal of all the hydraulic lines, fittings, hoses and clamps between the anti-skid valve and the left outboard brakes, as well as, the emergency brake line adjacent to the shuttle valve, the high pressure line to the brake relief valve and the brake assemblies. These components and assemblies should be retained for reinstallation following the completion of tests. Appendix I details step-by-step the removal of existing components, also shown in drawing 180-59850.

Following removal of the left, outboard brake system, the FHBS kit shall be installed. The kit shown schematically in Figure E.1, includes two brake assemblies, hoses, tubes, fittings, clamps, a reservoir/separator, a deboost valve, and mounting brackets. The brake assemblies and the deboost valve are identical to the removed components except they have been cleaned and resealed with modified "PNF" (phosphonitrilic fluoroelastomer) elastomer "O" rings. The hoses are PTFE lined for compatibility with the CTFE (Chlorotrifluoroethylene) hydraulic fluid. Appendix II details step-by-step the kit installation procedure, also shown in drawing 180-59850.

Flight test instrumentation interfaces are provided at two locations to sense hydraulic pressure. These interfaces are "T" fittings in the FHBS: one located between the anti-skid valve and the shuttle valve, and the second in the bleed port of the left, outboard forward wheel brake (which are shown in Figure E.1).

III. Instrumentation/Data Requirements

Boeing recommends, the following test instrumentation/data recording be taken during the flight test program:

Stopping distance

	L.H. Outbrd	L.H. Inbrd	R.H. Inbrd	R.H. Outbrd
Hyd. press. @ brake [2]	✓	*	*	✓
Wheel speed [3]	✓fwd A	✓fwd C	*fwd R	✓fwd L
	✓aft E	✓aft G	*aft N	✓aft J
Equalizer rod load [4]	✓	✓	*	✓
Antiskid valve hyd. press. [5]	✓	*	*	✓
Antiskid valve current [6]	✓U	*T	*Y	✓X

[1]

✓ minimum instrumentation/data

* optional instrumentation/data

"A" Modulating Antiskid Control Shield Connecter Pin "A" (Typ)

Additional test data that could be considered are:

- Wing mounted movie or TV camera [1] [7]
- Brake temperatures [1]
- Forward brake torques [1]
- Air speed (pitot-static pressure) [1]
- Runway weather station
- Forward/Aft g's [1]

[1] Time coordinated recordings

[2] AF provided hydraulic pressure transducer (0-1000 psi) (100 Hz response)

[3] Tachometer signal (0-3000 rpm) (50 Hz response).

[4] AF provided strain gaging of Equalizer Rods (35,400 pound max. operating design load) (100 Hz response)

[5] AF provided hydraulic pressure tranducer (0-3000 psi) (100 Hz response)

[6] Current signal from antiskid controller. (0-50 ma) (100 Hz response)

[7] For counting runway border lights (stopping distance) and/or photo record of wheels

IV. Recommended Test Conditions

Boeing recommends the following braking tests be accomplished during Phases I and II of the flight test program.

Condition No.	Gross Weight	Ground speed @ Brake Application	Remarks
1	150,000#	100 KTS	Dry runway
2	165,000#	100 KTS	Dry runway
3	180,000#	125 KTS	Dry runway
4	150,000#	100 KTS	Wet runway
5	165,000#	100 KTS	Wet runway
6	180,000#	125 KTS	Wet runway

Cooling fans will be utilized as required for brake cooling. Conditions 1 and 2 will be accomplished by accelerating to the designated speed in the takeoff configuration, then stopping. The airplane will be in normal landing configuration (flaps 50°) for conditions 3 through 6. Brakes will be visually inspected after each cooling period and brake temperatures, if instrumented, will be carefully monitored. All braking will be accomplished from the pilots seat utilizing maximum braking technique. Do not exceed brake limitations specified in the Flight Manual.

Maintenance instructions for the FHBS installation are specified for Fill and Bleed in Appendix II and Pre-flight Inspection in Appendix III.

V. Data Reduction and Success Criteria

Data recorded during the Phase I tests shall be used as a basis of comparison for the Phase II test data. The stopping distance versus gross weight shall be plotted for both phases. The wheel speed, brake pressure and anti-skid

current data from both phases as well as wheel to wheel data from Phase II shall be evaluated and compared to determine if excessive time skidding is occurring in the FHBS. The brake torque data and the computed braking energy shall be compared for performance equivalency.

Equivalent or better test aircraft stopping performance as determined from the brake torque data and braking energy shall be considered a successful demonstration of the FHBS.

APPENDIX I

Component Removal Requirements

The following is a list the components that require removal prior to installation of the FHBS kit. All the equipment to be removed is on the left main landing gear, and/or is associated with the outboard wheel pair.

Remove P/N	Nomenclature
5-87461-38	Tube Assy (Tee to Fuse)*
5-87461-504	Tube Assy (Fuse to Deboost)*
900-8-40	Fuse Assy
61-11501-2	Tube Assy (Anti-skid Valve to Deboost)*
5-96370-1	Deboost and Shuttle Valve Installation (Aft instl. in L.H. wheel well)
61-11505-2	Tube Assy (Deboost to Bulkhead Tee)*
AN804-6	Bulkhead Tee
61-11509-1	Tube Assy (Bulkhead Tee to Relief Valve)*
A50081AB61	Relief Valve
61-11748-2	Tube Assy (Bulkhead Tee to Strut Hose)*
AN833-8D	Elbow
MS28741-8-0290	Hose Assy (Fuselage to Strut)*
61-11534-1	Tube Assy (Strut Tube)*
AN837-8	Elbow (on Strut)
65-42808-5	Hose Assy (Strut to Truck/MS28741-8-0512 Hose Plus 65-42808-6 Nylon Braid)*
AN837-8	Elbow (on Truck)
61-11536-1	Tube Assy (Strut/Truck Hose to Truck Tee)*

61-11530-1	Tube Assy (Truck Tee to Fwd Brake)*
65-3081-5	Hose Assy (Aft Brake Hose/MS28741-6-0230 Hose Plus 65-3081-3 Nylon Braid)*
2600945	Brake Assy (Bendix P/N)(Left Outboard Fwd and Aft Assemblies)

* Also remove any clamps supporting this tube/hose assembly.

Drawing 180-59850 details the components to be removed. Store these components for reinstallation on the aircraft after completion of testing.

APPENDIX II

Fireproof Hydraulic Brake System Kit Installation Requirements

The following is an outline of the FHBS kit installation sequence for flight test. The complete assembly/installation of components may be found on drawing 180-59850.

Install 180-59998-1 Brake Assy on the left outboard, fore and aft axles. Reinstall wheels, etc.

Remove the P/N 146936 bleed valve from the forward brake assembly.

Install the bleed valve in the MS24389J3 instrumentation fitting and install the assembly in the forward brake assembly bleed port.

Install the following brackets:

180-59852-4	Shuttle Valve Bracket
180-59851-1, -2, -3, -4, -5, -6 & -7 180-59852-1, -2 & -3	Reservoir/Separator & Deboost Valve Support Brackets and Braces
180-59852-5 & -6	Tube Support Brackets - Main Gear

Rework clamp supports and bulkhead/bracket holes.

Install the MS24390J16, (2) MS24396J12, MS24388J8, MS24396J10 & MS24394J10 bulkhead fittings.

Install the 20349 Shuttle Valve to the 180-59852-4 Bracket with the bulkhead fitting.

Install MS24389J6 instrumentation fitting in Shuttle Valve port.

Install the 180-59837-1 Reservoir/Separator, the 180-59838-1 Deboost Valve to the mounting brackets with the appropriate fittings, fasteners and 180-59998-1 Clamp to the mounting brackets.

Install the following components to the Deboost and Reservoir/Separator Installation.

180-5984-1	Deboost/Fill Valve Tee
180-59843-1	Fill Valve
180-59839-1	Restrictor Check Valve
180-59840-1	Resistor Check Valve Adapter
MS24389J10	Bulkhead Tee
MS24391J10L	Bleeder Plug

Develop the annealled Aluminum pattern, larger diameter tubes utilizing the removed tubes as a pattern for the first cut. Continue the cut, bend and fit process until an Aluminum pattern tube fits all the interfaces (fittings, clamps, etc.) and has the proper clearances.
Using the Aluminum pattern tubes, bend carbon steel pattern tubes and flare ends. Check for fit at all interfaces. Identify the steel pattern tubes.
Manufacture the CRES tube assemblies per the following drawings using the appropriate pattern tube.

180-59848-1 Tube Assy - Strut/Truck Hose to Truck Tee
180-59849-1 Tube Assy - Truck Tee to Fwd Brake

180-59853-1 Tube Assy - Copilot Brake V. to Shuttle V.
180-59854-1 Tube Assy - Anti-skid Valve to Shuttle V.
180-59855-1 Tube Assy - Shuttle V. to Res/Sep.
180-59856-1 Tube Assy - Deboost V. to Bleed Tee
180-59857-1 Tube Assy - Bleed Tee to Blkhd Tee
180-59858-1 Tube Assy - Blkhd Tee to Relief V.
180-59859-1 Tube Assy - Blkhd Tee to Body/Strut Hose
180-59860-1 Tube Assy - Strut Tube

Clean fittings by flushing with Stoddard Solvent and blow dry.
Install tubes and hoses.
Install instrumentation transducers and adapters provided by AF near the shuttle valve and forward brake.

Fill and bleed the test aircraft per Figure E.1 and the following:

1. Fill and bleed the left and right hydraulic systems.

NOTE: Be careful to prevent the reservoir from becoming empty and allowing air to enter the lines. Connect external electrical power and monitor the hydraulic reservoir gages.

2. Loosen the right hydraulic system reservoir cap three turns and place a clean container under reservoir drain.

3. Connect external electrical power per T.O. 1C-135A-2-1 and pressurize the right hydraulic system to 100 psi with a ground power cart. Apply and then release the copilot's brake pedals.

4. Maintain 100 psi upstream of the FHBS reservoir/separator and bleed fluid/air from the bleed plug above the reservoir/separator until the fluid flows free of air bubbles. Reduce pressure to zero.

NOTE: Line leading to brake relief valve may be bled, if required, by loosening line at valve inlet until fluid flows from line. Tighten line with fluid still flowing.

5. Repeat 3 and 4 for left hydraulic system and pilot brake pedals then tighten bleed fitting.

6. Connect the CTFE service cart to the forward left outboard brake bleed fitting and open the aft brake bleed fitting. Pump CTFE fluid into the system until fluid flows from aft wheel bleed fitting, then close the aft bleed fitting and remove service cart from forward brake fitting.

7. Connect the service cart to the aft brake bleed fitting. Open the forward brake bleed fitting and pump CTFE fluid into the system until the bleed fluid flows free of air, then close.

8. Open the "high point" bleed fitting near the wheelwell bulkhead tee and continue to pump CTFE fluid into the system until the bleed fluid flows free of air, then close bleed valve and disconnect CTFE cart.

9. Reconnect the CTFE fill cart to the FHBS/CTFE system fill valve just below the deboost valve. Pump in CTFE fluid until reservoir/separator level is 100%.

10. Remove the cap from the CTFE system bleed valve at the end of the reservoir/separator rod, connect a drain tube and open valve.

11. Open the "high point" bleed fitting near the bulkhead fitting. Pump in CTFE fluid until fluid free of air bubbles starts to drain from either location then close that fitting and continue to fill system until fluid, free of air bubbles, flows from the other fitting then close it.

12. Close the CTFE fill valve.

13. Pressurize the right hydraulic power system to 100 psi and cycle the copilot brake pedals 25 times.

NOTE: Fluid collected on the shoulder of the brake deboost valve piston will be forced out the deboost valve vent screen during bleeding procedure. Continuous flow of fluid out the vent screen could indicate a faulty valve.

14. While holding down the copilot pedals bleed the left outboard forward brake, then the aft brake, then the "high point" bleed plug near the bulkhead tee and last the reservoir/separator bleed valve.

NOTE: Check the reservoir/separator level after each bleeding. If the CTFE fluid level indicated is less than 40% refill to 80% before proceeding. Refilling the reservoir/separator is accomplished by removing the copilot brake pedal pressure and pumping CTFE fluid from the fill cart into the FHBS/CTFE fill valve just below the deboost valve.

15. Reduce the right hydraulic system pressure to zero. Check the reservoir/separator level and replenish the level to 80% as required.

16. After ten minutes minimum repeat paragraphs 13 through 15. Continue repeating until no air bubbles are evident in the bleed fluid.

17. Release copilot's brake pedals and return right system pressure switch to "off".

18. Pressurize left and right hydraulic systems to 3000 psi.

19. Close "OUTBD ANTI-SKID" circuit breaker on main circuit breaker panel.

20. Depress the pilot's brake pedals and hold this position for at least one minute to allow air to bleed from the brake pressure line between the pilot's brake metering valve and the anti-skid valve.

21. Release pilot's brake pedals and open "OUTBD ANTI-SKID" circuit breaker.

22. Apply the pilot's brakes at least five times to a level just sufficient to move the brake pressure plates against the heat stacks. Release brakes completely between applications allowing the pressure plates to fully retract. Wait 30 seconds between applications. On the final application, hold enough pressure to keep the pressure plates against the heat stacks and bleed two to three ounces of fluid from each brake.

23. Depress pilot's brake pedals. While pilot's brake pedals are being held down, depress copilot's brake pedals. Hold copilot's brake pedals down and release pilot's brake pedals.

24. The shuttle valve is now in the "pilot's side blocked" position. Release the copilot's brake pedals. Repeat this step several times to force air from the line between the anti-skid valve and reservoir/separator through the Right Hydraulic System return lines to the reservoir.

25. Depressurize both hydraulic system ground power carts.

26. Pressurize the left system to 3000 psi with a ground power cart and exercise the pilot's brake pedals. Inspect FHBS installation for leakage. Depressurize left system.

APPENDIX III

FHBS Pre-Flight/Post-Flight Inspection

FHBS Pre-Flight Inspection (Left Main Gear Outboard Wheel Pair)

Inspect brakes per normal pre-flight procedures.
Inspect brakes for CTFE fluid leaks.

Note: Close inspection is required since the CTFE fluid is clear (uncolored).

Inspect brake bleed valves for leakage and proper installation of dust caps.
Inspect main gear truck tubes, connectors and hoses for abrasion or leakage.
Inspect Reservoir/Separator for excessive leakage from the side weep holes and rod seal. Note: Light leakage is allowed from weep holes.
Inspect Deboost Valve vent screen for excessive leakage.
Inspect bleed plugs and bleed and fill valves for leakage and proper installation of dust caps (as applicable).
Check for an 80% Reservoir/Separator fluid level on gage.

FHBS Post-Flight Inspection (Left Main Gear Outboard Wheel Pair)
Caution: Brakes and wheels may be very hot for an hour or more following braking.
Inspect brakes per normal post-flight procedures.
Inspect brakes for CTFE fluid leaks.
Note: Close inspection is required since the CTFE fluid is clear (uncolored).
Inspect the Reservoir/Separator and Deboost Valve assemblies for excessive leakage from the weep and vent holes.
Check for 80% Reservoir/Separator fluid level on gage.

Note: Fluid level may be above 80% if the FHBS/CTFE fluid is hot from recent braking.

APPENDIX III

FHBS Pre-Flight/Post-Flight Inspection

FHBS Pre-Flight Inspection (Left Main Gear Outboard Wheel Pair)

Inspect brakes per normal pre-flight procedures.
Inspect brakes for CTFE fluid leaks.

Note: Close inspection is required since the CTFE fluid is clear (uncolored).

Inspect brake bleed valves for leakage and proper installation of dust caps.
Inspect main gear truck tubes, connectors and hoses for abrasion or leakage.
Inspect Reservoir/Separator for excessive leakage from the side weep holes and rod seal. Note: Light leakage is allowed from weep holes.
Inspect Deboost Valve vent screen for excessive leakage.
Inspect bleed plugs and bleed and fill valves for leakage and proper installation of dust caps (as applicable).
Check for an 80% Reservoir/Separator fluid level on gage.

FHBS Post-Flight Inspection (Left Main Gear Outboard Wheel Pair)
Caution: Brakes and wheels may be very hot for an hour or more following braking.
Inspect brakes per normal post-flight procedures.
Inspect brakes for CTFE fluid leaks.
Note: Close inspection is required since the CTFE fluid is clear (uncolored).
Inspect the Reservoir/Separator and Deboost Valve assemblies for excessive leakage from the weep and vent holes.
Check for 80% Reservoir/Separator fluid level on gage.

Note: Fluid level may be above 80% if the FHBS/CTFE fluid is hot from recent braking.

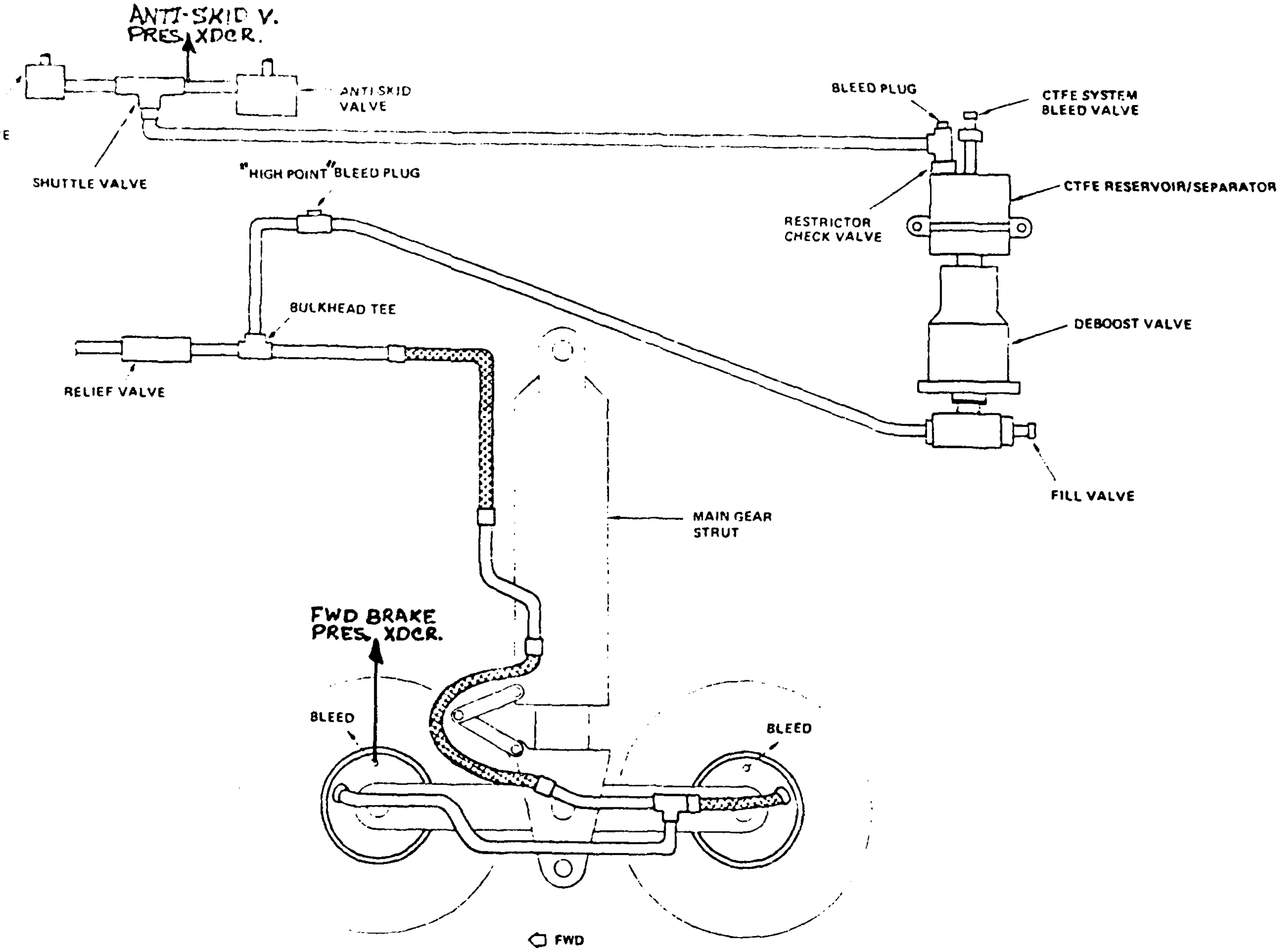

FIGURE E.1. FHBS Schematic with Recommended Test Instrumentation

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